A CAPP SYSTEM FOR FINE AND FINISH GRINDING

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CERTIFICATE

This is to certify that the work contained in this thesis entitled "**A CAPP System for Fine and Finish Grinding**", by **Rajesh Kumar Burman**, has been carried out under our supervision and that this work has not been submitted elsewhere for the award of a degree.

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ABSTRACT

In the present work, computer aided process planning system has been developed for fine grinding using generative approach. The system consists of four modules. First module for feature recognition receives the input in the form of primitives for features on the workpiece surface and decides the type of grinding process to be employed. Second module assists the user in selection of workpiece material. Third module carries out the selection of grinding wheel using various databases. Fourth module determines the operating parameters like table speed and depth of cut for the case of surface grinding and external cylindrical grinding only. The system has been developed in ANSI C standards using Borland C++ compiler and has been implemented on IBM compatible PC-AT/XT.

Dedicated
to
my parents

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Rajesh Kumar Burman

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NOMENCLATURE

A'	Man-machine cost per unit grinding wheel width, unit cost/sec/mm.
c	Specific heat of the workpiece material, J/kg.K.
C'	Dressing cost per cycle per unit grinding wheel width, unit cost/cycle/mı
C_1	Constant.
C_2	Constant.
d	Depth of cut, mm.
f	Exponent relating grinding force and equivalent grinding thickness.
$f(x,y)$	Objective function.
F_1	Reference tangential force, N/mm.
F_t	Tangential grinding force per unit wheel width of cut, N/mm.
$F(x,y)$	Penalized function.
$g(x,y)$	Constraint function.
h_1	depth of concave surface.
h_2	height of concave surface.
k	Thermal conductivity of the workpiece material, W/m.K.
l	Length of cut, mm.
l_1	Length of spread of concave surface, cm.
l_2	Length of spread of convex surface, cm.
m	length of cylindrical workpiece.
n	radius of cylindrical workpiece.
P	Power required for grinding, Watts.
q	Enegy dissipated at interface per unit area per unit time, Watt/mm^2.
r	Exponent relating surface roughness and equivalent grinding thickness.
R	Surface roughness, microns.
R_1	Reference surface roughness, microns.
u	Specific grinding energy, J/mm^3.
u_j	Penalty coefficient.
v	Table speed, m/sec.
V	Grinding wheel speed, m/sec.
V_1	Constant, mm^3/mm.
z	material removal rate per unit wheel width, mm^2/sec.
z'	Total cost per unit stock removal, unit cost/mm^3.
μ	Coefficient of friction.
ν	Exponent relating wheel life and equivalent grinding thickness.
θ	Mean temperature for a unit width of wheel-work contact.
ρ	Density of the workpiece material, kg/m^3.

Chapter 1

INTRODUCTION

1.1 Grinding

Grinding is the common name for machining processes which utilize hard, sharp and friable abrasive grains as the cutting tool. The grinding process for providing required shape to the materials is probably the oldest in existence. Dating from the time prehistoric, man found that he could sharpen his tools by rubbing them against gritty rocks. Today, grinding is one of the precision machining methods which is applied to final finishing in mechanical machining processes and its importance has been increasing in recent years with growing demand for higher level of accuracy in the machining industry. Almost everything that we use has either been machined by grinding at some stage of its production, or has been processed by machines which owe their precision to grinding operations.

Grinding wheels are generally composed of two materials: tiny abrasive particles called grains or grits, which do the cutting, and a softer bonding agent to hold the countless abrasive grains together in a solid mass. Grinding removes metal by cutting as do single point tools but the difference exists in that grinding is a self-sharpening process. As the grains or grits wear during cutting, they either fracture or tear off the wheel bond, exposing new and sharp cutting edges.

Of all the machining processes in common use, grinding is undoubtedly the least understood and most neglected in practice. The stray dispersion of grains along the periphery of the wheel and their random geometry make the grinding process too

complex to be defined by mathematical models. Mathematical modelling is a way of representing the grinding process away from the shop floor. Grinding is largely planned on the basis of machinists' experience rather than experimental results or well-authenticated theories. However due to relentless effort of researchers all over the world, now, there is sufficient amount of well-authenticated observations to enable formulation of at least an over-simplified model of grinding process.

But these mathematical models can be used only as far as selecting operating parameters is concerned. The selection of grinding wheels still remains out of the purview of mathematical models. There has been dependence on the know-how of skilled technician or on machining handbook and database. This led to the concepts of thumb rules and a reasonably well established database. Both of these are based on the machinists' experience and suggestive results from controlled experiments (Rao, 1990).

An average intelligent human being adopts the thumb rules and database with varying weightage on various aspects of approach. The same process planning engineer might give two different solutions for the same problem at different times when he judges his decision on the basis of thumb rules. A review of the process plans in the industry shows that process plans are inconsistent, often for no apparent logical reason. This inconsistency coupled with the problem of estimating the parameters of grinding optimally, necessitated the use of computers for developing process plans for grinding processes.

So far, the thumb rules for grinding wheel selection and mathematical models for determination of grinding parameters do not have well defined links. To simplify the problem, the domain is confined to fine grinding to eliminate the factors of workpiece geometry complexity and process complexity.

The present work attempts to give a complete picture for fine grinding using all grinding processes *viz.* external cylindrical grinding, internal cylindrical grinding, surface grinding and centreless grinding. It is hoped that it would be an attractive solution in area of process planning of grinding.

1.2 Process Planning

1.2.1 Definition

Process planning is the function within a manufacturing facility that establishes which manufacturing processes and parameters are to be used (as well as those machines capable of performing these processes) to convert (machine) a piece part from its initial form to a final form predetermined (usually by a design engineer) from an engineering drawing. Related to process planning are the functions of determining appropriate and optimal cutting conditions for machining operations. These functions which have been traditionally carried out manually, are presently being performed with the aid of computer, leading to the emergence of computer aided process planning (CAPP).

Since the process planning requires a great deal of judgement, even among the experienced engineers, there has been variation in the judgement for the same product. To minimize the dependence on human skill and inevitable variances in judgement, computer based approach is used in manufacturing environment. Attempts to incorporate logic, judgement and experience required for process planning in computer programs have largely helped in automation of process planning.

1.2.2 Process Planning Approaches

Two approaches to computer aided process planning are traditionally recognized: the variant approach and the generative approach. However with the rapid development of new techniques, many CAPP systems do not easily fit this classification and combine both approaches (Chang and Wysk, 1985).

Variant Approach

The variant approach to process planning is comparable with the traditional manual approach where a process plan for a new part is created by recalling, identifying and retrieving an existing plan for a similar part and making the necessary modifications for the new part. In some variant systems, parts are grouped into

a number of part families, characterized by similarities in manufacturing methods and thus related to group technology. For each part family, a standard process plan, which includes all possible operations for the family is stored in the system. The standard plan is retrieved and edited for the new part.

Generative Approach

In generative approach, process plans are generated by means of decision logic, technology algorithms and geometry based data to perform uniquely the many processing decisions for converting a part from raw material to a finished state. The rules of manufacturing and the equipment capabilities are stored in a computer system. When using the system, a specific process plan for a specific part can be generated without any involvement of a process planner. Inputs to system would include a comprehensive description of the workpiece. This approach does not involve the retrieval of existing process plans.

1.2.3 Process Planning for Grinding

Lot of work has been done in the area of computer aided process planning for various conventional machining processes. Relatively less attention has been paid to the development of CAPP for grinding process. However, due to persistent work of researchers, grinding process has been lately brought under purview of CAPP systems to some extent.

As in case of other processes, both types of process planning *viz.* variant and generative type can be developed for the grinding process. Variant type is usually developed when a component or components of the same design and manufacturing characteristics are to be developed frequently. Generative type is preferred when there is very less probability of the same type of component being produced repeatedly.

For a given material and required surface finish, the process plan for grinding involves:

1. determining whether the given workpiece is machinable on the available

grinding machine tools.

2. determining whether the required surface finish is attainable on the available grinding machine tools.

3. identifying the type of grinding process to be used.

4. grinding machine selection for each operation.

5. selecting the grinding wheel for each operation.

6. setting optimal cutting conditions for each operation, like table speed, depth of cut and cross feed.

7. determining grinding parameters like:

    - number of passes required for each operation.
    - total number of passes required before wheel needs dressing.
    - wheel life.
    - total time required for machining.
    - total number of dressings of the wheel required to finish the operation.
    - forces and power required for each operation.

With the introduction of the concepts of "equivalent diameter", the three grinding processes *viz.* external cylindrical, internal cylindrical and surface grinding are no longer considered to be separate for the purpose of cutting conditions and grinding parameters determination. For internal and external cylindrical grinding, peripheral speed has to be reported instead of table speed as is done in surface grinding.

1.3 Literature Survey

Although most of the research work in grinding contributed to some specific areas, there are some attempts to give explanation on a broad perspective.

Anbarasu developed in 1988 an expert system for fine surface grinding. However, in this approach, empirical formulas were used for determining grinding parameters.

In 1970, Des Ruisseaux and Zerkle investigated temperature in the vicinity of chip formation and related this temperature to the temperature experienced by the workpiece surface. They tried to correlate this heat energy in the grinding zone to tangential force.

Malkin proposed in 1976 a model for selection of operating parameters for surface grinding of steels, giving more weightage to workpiece as constraints on grinding wheel tool life. The results indicated that it is best to use the maximum allowable workpiece velocity with a corresponding optimum downfeed which is larger for slower workpiece velocity.

Malkin and Koren developed in 1980 a model for optimization of plunge grinding operations on steels. They used the constraints of workpiece burn and surface finish to be developed on the workpiece.

Rao developed in 1990 computer aided process planning system for fine grinding using generative approach and formulated a non-linear optimization model for determining the cutting conditions.

Tonshoff et al. presented in 1992 topography models, chip thickness models, grinding energy model, force model, temperature, surface integrity and roughness models based on earlier works.

Trmal et al. developed in 1992 an expert system based on a grinding database and a knowledge base. He used a model which takes into account a number of factors dependent on the input conditions. The system was used for optimization by comparing predictions for a variety of input conditions.

Younis, Sadek and Wardani developed in 1987 semi-empirical expressions for force by dividing them into three components *viz.*, plowing, rubbing and cutting. The effect of loading was also taken into consideration.

Zohdi developed in 1974 mathematical model to estimate the surface finish. Physical experimentation coupled with subsequent statistical analysis were applied

to further the understanding of the process. Optimum results that lead to the best surface finish with the maximum rate of material removal were discussed and evaluated.

1.4 Present Work

In the present work, an attempt has been made to develop computer-aided process planning for fine grinding using generative approach. Feature recognition is carried out on the workpiece surface to find out the type of grinding to be used. In the next step, grinding wheel is selected using various databases and data from industrial experience. Optimization model has been developed using genetic algorithm technique to find out the optimum values of work speed and depth of cut required during grinding.

The present software has been developed in four modules. The first module receives the necessary input data about the part geometry and recognizes the features. The code for workpiece material is entered in the second module. The third module carries out the selection of grinding wheel based on the first two modules. Optimal grinding parameters are obtained in the fourth module. All the modules have been developed in ANSI C standards using Borland C++ compiler and have been implemented on IBM compatible PC-AT/XT.

1.5 Organization of the Thesis

The organization of thesis report is as follows:

Chapter 2 discusses about the analysis of the system i.e. the basic parameters affecting the performance of the grinding wheel, decision variables and the limitations which has to be applied while determining the grinding conditions.

Chapter 3 deals with the design of process planning system consisting of selection criteria of grinding wheel, grinding process and the optimization model.

Chapter 4 gives the details of the implementation of the proposed system and results for two test examples.

Chapter 5 concludes with the scope for future work.

Chapter 2

ANALYSIS OF GRINDING PROCESS

This chapter discusses about the analysis of grinding process, the parameters influencing the performance of grinding wheel and the constraints on the decision variables to determine the operating parameters.

2.1 Basic Wheel Parameters

In this section, the constituents of grinding wheel and the parameters affecting the grinding wheel performance are discussed.

For manufacturing grinding wheel, the abrasive grains are mixed with a bonding agent and pressed or cast into the required shape and baked in the electrical furnaces. The performance of grinding wheel depends upon the following parameters:

1. Type of abrasive grains.
2. Size of abrasive grains.
3. Wheel hardness.
4. Spacing between grains.
5. Type of bonding.

The influence of these parameters on grinding wheel selection is explained in the following sub-sections.

2.1.1 Abrasive Type

Abrasive grains are natural or synthetic materials which are generally much harder than the materials which they cut. Natural abrasives include aluminium oxide (natural corondum and emery), garmet and diamond. Technological advances in the abrasive industry have been mainly in the development of synthetic abrasives.

Virtually all conventional abrasives in use today on grinding wheels are synthetic materials based upon either aluminium oxide (Al_2O_3), or silicon carbide (SiC). The hard aluminium oxide phase is alpha-alumina, having an hexagonal crystal structure like that of natural oxide abrasives (emery and corondum). In addition to Al_2O_3, synthetic aluminium oxide contain various amounts of other metallic oxides either intentionally added or as impurities. Silicon carbide occurs in various polytypes, which can be generally classified as alpha-types having hexagonal or rhombohedral crystallographic structures and a beta-type which is cubic (Malkin, 1989).

Harder abrasive grains are generally more friable. Silicon carbide abrasives are harder than aluminium oxide, and also tend to fall towards the upper end of the friability range. Harder and more friable abrasives are generally applied to precision grinding operations.

2.1.2 Abrasive Grain Size

Abrasive grain size is indicated by a grit number which is related to the mesh number (specified as wires per linear inch) of the screen used to sort the grains. A larger number indicates a smaller grain size. Sieving (screening) is generally used for sizing of grains coarser than 240 grit size, whereas sedimentation method is used for finer grains.

The grit dimension d_g can be found out from the relationship (Malkin, 1989).

$d_g = 15.2\ (s)^{-1}$
where d_g is in mm.

Coarse grits are in the range of 6 to 24, medium from 30 to 60, fine from 70 to 180, and very fine from 220 and above.

2.1.3 Wheel Grade

The wheel grade or hardness provides a general indication of wheel strength and the degree to which abrasive grains are tightly held by the binder. This property is interpreted as the force required to dislodge a grain from the bond. The greater the bond content, the 'harder' the wheel. The wheel grade is designated by the letters of the alphabet. A very 'soft' wheel readily looses the grains and is denoted by the letter 'A' while 'Z' is used for very hard wheels. For smaller area of contact, harder grade is preferred.

2.1.4 Wheel Structure

The structure number in the wheel marking indicates the volumetric concentration of abrasive grain in the wheel, a higher number indicating less abrasive or more open wheel. The volumetric composition of the grinding wheel can be expressed in terms of V_a, the percentage volume of abrasive grains, V_b, the percentage volume of bond material and V_c, the percentage volume of pores. These three constituents can be altered to control the wheel structure and the grade or hardness (Malkin, 1989).

The structure is called dense when V_a is high and open when V_a is less. Lower number indicates a dense structure. The American Standards recommends numbers ranging from 1 to 15. Surface grinding requires more open structure than cylindrical grinding.

2.1.5 Bond Material

Abrasive grains are held together with various kinds of bond materials. The bond

- must be strong enough to withstand grinding forces, temperatures, and centrifugal forces without disintegrating,

- must be rigid enough to enable the grit to penetrate and cut the work at the prescribed depth of cut,

- should be able to retain abrasive grains during cutting yet release dulled grains, and

- must be able to resist chemical attack by the cutting fluid.

According to the wheel marking system, there are five general types of bond materials for conventional grinding wheels: resinoid denoted by 'B', vitrified denoted by 'V', shellac denoted by 'E', rubber denoted by 'R', and silicate denoted by 'S'.

Vitrified bond probably account for about half of all conventional abrasive wheels. Vitrified bonds are formed from mixtures of clay and feldspar. Resinoid bonded wheels are produced by mixing abrasive grains with phenolic thermosetting resins and plasticizers, moulding to shape, and curing (baking) at 150 - 200 °C. Rubber bonds consist of vulcanized natural or synthetic rubber. Silicate bonded wheels are manufactured by mixing sodium silicate with abrasive, tamping in a mould, drying and baking. Shellac bonded wheels can be manufactured by mixing abrasive grains with shellac, shaping under pressure in heated moulds, and baking. Shellac bonds are rarely used (Malkin, 1989).

2.1.6 Grinding Wheel Specification

A wheel marked as A - 46 - M - 6 - V - 10 represents an aluminium oxide grit of 46 mesh size. The wheel is a medium grade with a fairly open structure and a vitrified bond. The last number in the specification shows the manufacturer's number for identification purposes.

2.2 Salient Parameters of Grinding Process

In heavy duty grinding operations, where surface quality is not important, stock removal rates are generally limited by capacity of the machine and breakdown of the grinding wheel. In fine grinding operations, surface finish on the workpiece surface is more important, therefore allowable material removal rate is much less. Material removal rate per unit width of grinding wheel for all three grinding processes: external cylindrical, internal cylindrical and surface grinding is given by

$$z = vd \tag{2.1}$$

where z is the material removal rate per unit grinding wheel width, v is the table speed, and d is the depth of cut.

In surface grinding, the depth of cut is downfeed per pass of workpiece under wheel. In external and internal grinding, depth of cut is infeed of wheel per revolution of workpiece. The various decision variables are discussed in the subsequent sections.

2.2.1 Temperature

Figure 2.1 represents chip formation in surface grinding process. At the beginning of the interference zone, where a grain first contacts with the workpiece, sliding and plowing of the workpiece surface by a grain can occur. At this location, forces are not sufficiently large to remove material. As the grain moves along the workpiece, it encounters a thick layer of uncut material, forces increase, and a chip is removed. At every location of the grain on the workpiece, there is heat generated between the grain and material because of frictional sliding. There is also heat generated in the material which is being plastically deformed. As the chip travels up the rake face of the grain, heat is generated between the chip and the grain. Thus temperatures of large magnitude can occur in the vicinity of cutting edges. Based on the preceding discussion, the workpiece could be considered to

be subjected to a continuously acting distributed heat source. Jaeger's analysis of moving heat source on semi-infinite body provides basis for temperature calculations. The model of Jaeger's analysis is shown in Figure 2.2. A perfect insulator of length l with a band heat source of uniform intensity at its lower surface q is considered to move with constant velocity v across a semi-infinite stationary body having thermal conductivity k and volume specific heat ρc. The mean temperature for a unit width of wheel-workpiece contact can be expressed as

$$\theta = \frac{uvd}{[vl(k\rho c)_w]^{0.5}} \tag{2.2}$$

Suffix w is for the workpiece. Here l is the length of contact given by $l = \sqrt{dD_e}$, θ is the mean temperature for a unit width of wheel-work contact, u is the specific grinding energy, k is the thermal conductivity of the workpiece material, ρ is the density of the workpiece material, c is the specific heat of the workpiece material, and D_e is the equivalent diameter. Values of k, ρ and c for workpiece are taken from Metal's Handbook. For 100Cr6 steel, $k = 60$ W/m.K, $\rho = 7800$ kg/m^3, and $c = 450$ J/kg.K. For 4615 steel, $k = 50$ W/m.K, $\rho = 7850$ kg/m^3, and $c = 490$ J/kg.K. For 316 steel, $k = 16.3$ W/m.K, $\rho = 8050$ kg/m^3, and $c = 430$ J/kg.K.

The thermal capacity of importance is $(k\rho c)^{0.5}$ for the work. While this combination of thermal properties does not have a common name, it is recognized as the geometric mean of thermal conductivity and volume specific heat and hence will be referred to as geometric mean thermal property (GMTP) (Des Ruisseaux, 1970, Shaw, 1990).

2.2.2 Grinding Forces

The grinding force components are generated in three stages: rubbing, plowing and cutting as represented in Figure 2.3 on a force diagram at the tip of a single grit along the wheel workpiece contact. The cutting force components can be expressed in terms of equivalent chip thickness as:

Tangential force $F_t = F_1 {h_{eq}}^f$

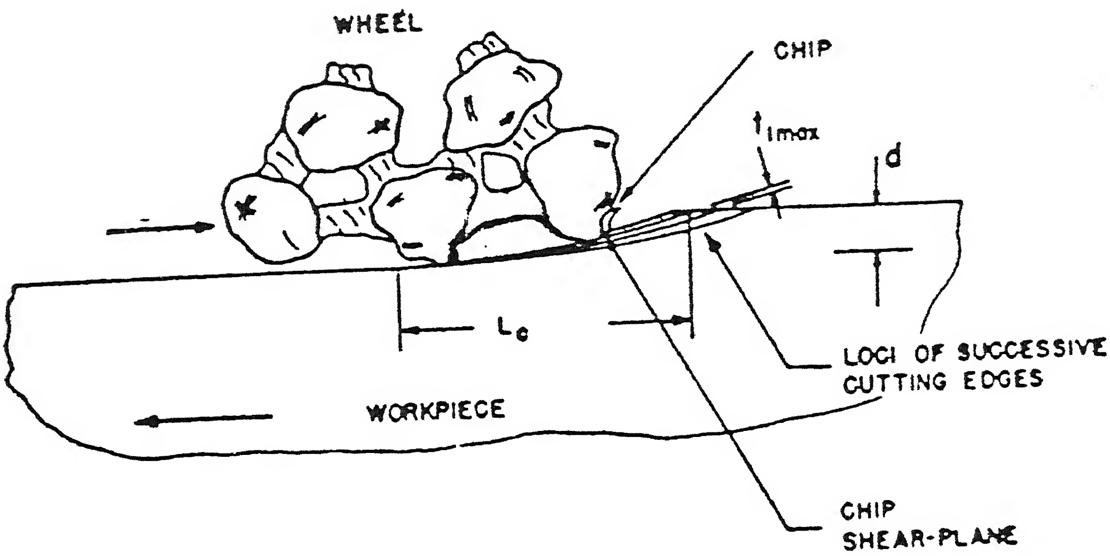


Figure 2.1: Chip formation process (Des Ruisseaux, 1970).

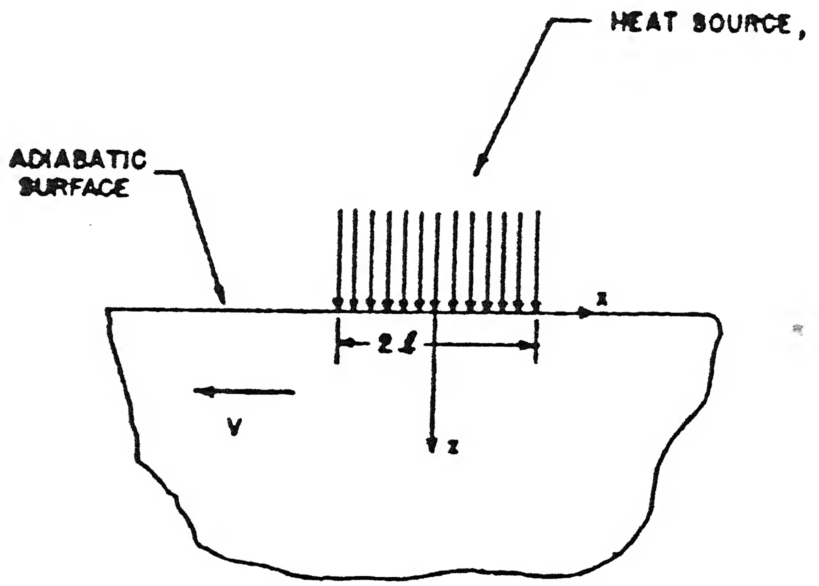


Figure 2.2: Band heat source on semi-infinite body (Des Ruisseaux, 1970).

Normal force $F_n = \frac{F_1}{\mu} h_{eq}{}^f$

F_1 is the reference tangential force depending on equivalent diameter and to a small extent on the velocity ratio. f is the exponent relating grinding force and equivalent chip thickness, and μ is the coefficient of friction. Values for F_1, f and μ for different materials can be taken from grinding charts as given in Appendix A (Snoeys and Peters, 1974).

2.2.3 Specific Energy

Energy expended during grinding arises from three processes: chip formation, plowing and sliding. Therefore specific grinding energy can be expressed as: $u = u_{ch} + u_{pl} + u_{sl}$.

Specific chip formation energy is energy required to remove a unit volume of material by chip formation.The specific energy for cutting, which is that portion of specific grinding energy remaining after subtracting the contribution due to sliding and plowing can now be calculated from relationship

$$u_{chip} = \frac{F_t.V}{b.v.d} \qquad (2.3)$$

where b is the grinding wheel width, V is the grinding wheel speed, and d is the depth of cut.

At slow removal rates, specific cutting energy is extremely high, but it decreases at faster removal rates. It has been found that shearing energy accounts for about 75% of the chip formation energy which can be approximated by the energy to melt a unit volume of workpiece material.

Specific plowing energy is expended by deformation of workpiece material without removal. Plowing include plastic deformation of material passing under the cutting edge. This occurs when the abrasive initially starts to cut into the workpiece (Malkin, 1989).

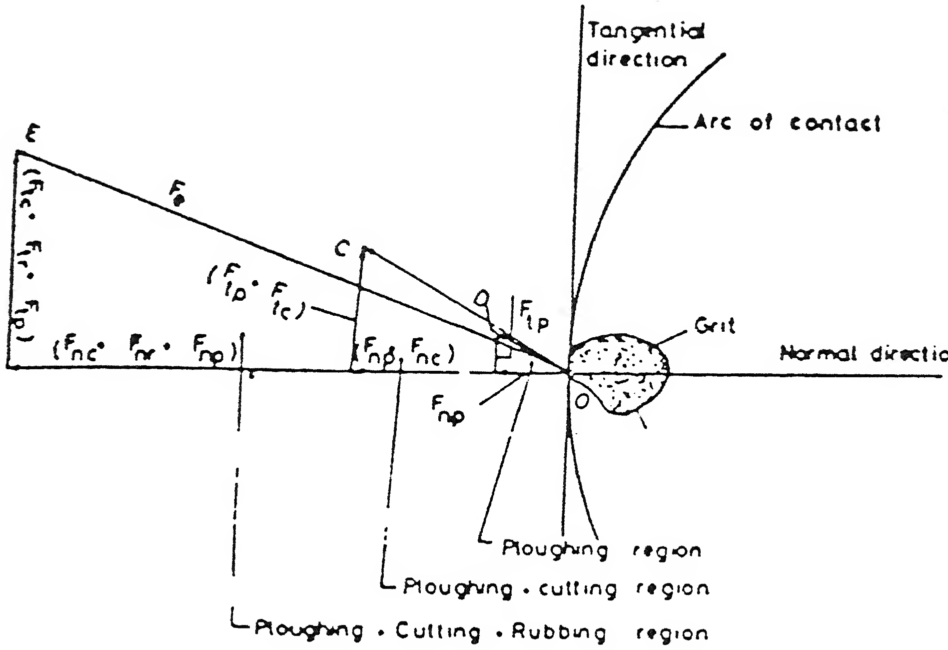


Figure 2.3: Force diagram at the tip of a single grit (Younis et al., 1987).

2.2.4 Residual Stresses

Residual stresses are induced by non-uniform plastic deformation near the workpiece. Mechanical interactions of abrasive grains with the workpiece result in predominantly residual compressive stresses by localized plastic flow. Residual tensile stresses are caused mainly by thermally induced stresses and deformation associated with the grinding temperature and its gradient from surface into the workpiece (Malkin, 1989). The influence of residual stresses is relatively more pronounced with higher strength brittle materials. Residual compressive stresses are considered to have a beneficial affect on mechanical strength properties, whereas residual tensile stresses adversely affect the strength of the workpiece.

2.2.5 Workpiece Burn

Excessive grinding temperatures cause thermal damage. One of the most common types of thermal damage is workpiece burn. It is essentially a kind of irreversible change of microstructure of workpiece surface layer taking place under the action of continuous high temperature at the grinding zone. At the onset of burning, there is a tendency for increased adhesion of metal particles to the abrasive grains, thereby causing the forces to grow, the workpiece surface to deteriorate, and the rate of wheel wear to increase with burning. Rehardening of steel also occurs.

Workpiece burn will limit maximum working temperature and maximum specific grinding energy. When burning occurs, it generally becomes necessary to reduce the grinding power by lowering the material removal rate, by using a coarser dressing condition, or by changing to a softer wheel grade. For a given machine setting, it is found that the grinding force components normal and tangential to the workpiece surface increase linearly with the wear flat area upto burning condition, beyond which, the increase with wear flat area becomes much steeper (Des Ruisseaux, 1970, Malkin, 1989).

2.3 Constraints on Decision Variables

The material removal rates for three types of grinding process: external cylindrical, internal cylindrical and surface grinding is given by equation (2.1). In stock removal grinding operations, where surface quality of the workpiece is not the main criteria, maximum possible values of peripheral speed and depth of cut should be used limited by grinding wheel breakdown.

In fine grinding operations, allowable material removal rates are much smaller due to surface quality requirements in the finished part. Increase in the table speed and depth of cut will increase material removal rate which will affect the surface finish required on the workpiece. Therefore a proper balance has to be maintained between the material removal rate and the surface finish required.

One main limitation to the removal rate for grinding is workpiece burn. On the basis of a heat transfer analysis and experimental measurements, it has been shown that burning occurs when a critical grinding zone temperature is reached. Temperatures of high order are experienced in grinding operations. More than 80% of heat generated in the process is pumped into the workpiece which results in rising of workpiece temperature. As the peripheral speed or depth of cut or both increases, the heat generated in the process also increases. At a particular stage, when the temperature in the wheel-workpiece interaction zone reaches the oxidation temperature of workpiece material, workpiece burn occurs. Therefore constraint has to be put on the value of temperature (Rao, 1990).

There should be a constraint on the roughness value of the workpiece which will be limited by the maximum surface finish required. Apart from this there has to be a limitation on the value of tangential force.

From the above discussion it is clear that values of peripheral speed and depth of cut has to be determined in such a way that

- workpiece burn does not occur, and
- required surface finish is maintained.

The optimal values for cutting conditions are determined by formulating and

solving optimization problem subjected to constraints which are also written in terms of cutting conditions. The grinding wheel speed is usually kept constant for the case of fine grinding. Thus it is not taken as a decision variable.

Further, dimensional tolerance has not been included as input for process planning. Surface finish requirements on various surfaces of a part, however, have been included in the system.

A CAPP model based on the aforesaid considerations is discussed in the next chapter.

Chapter 3

DESIGN OF PROPOSED CAPP SYSTEM

The proposed CAPP system comprises:

1. feature recognition on the workpiece surface for finding out the type of grinding required,
2. input for the workpiece material,
3. selection of grinding wheel, and
4. determination of optimal operating parameters like depth of cut and work speed.

Figure 3.1 shows the system flow chart for the proposed CAPP system. The various modules are dealt with in subsequent sections.

3.1 Feature Recognition

As the first step, program takes the input in the form of the name of the part and number of surfaces on which grinding has to be done. Before grinding operation, one has to find out which type of grinding method is to be employed. This is based on the features on the workpiece.

For providing inputs for feature recognition the three popular methods are:

- by coordinates,

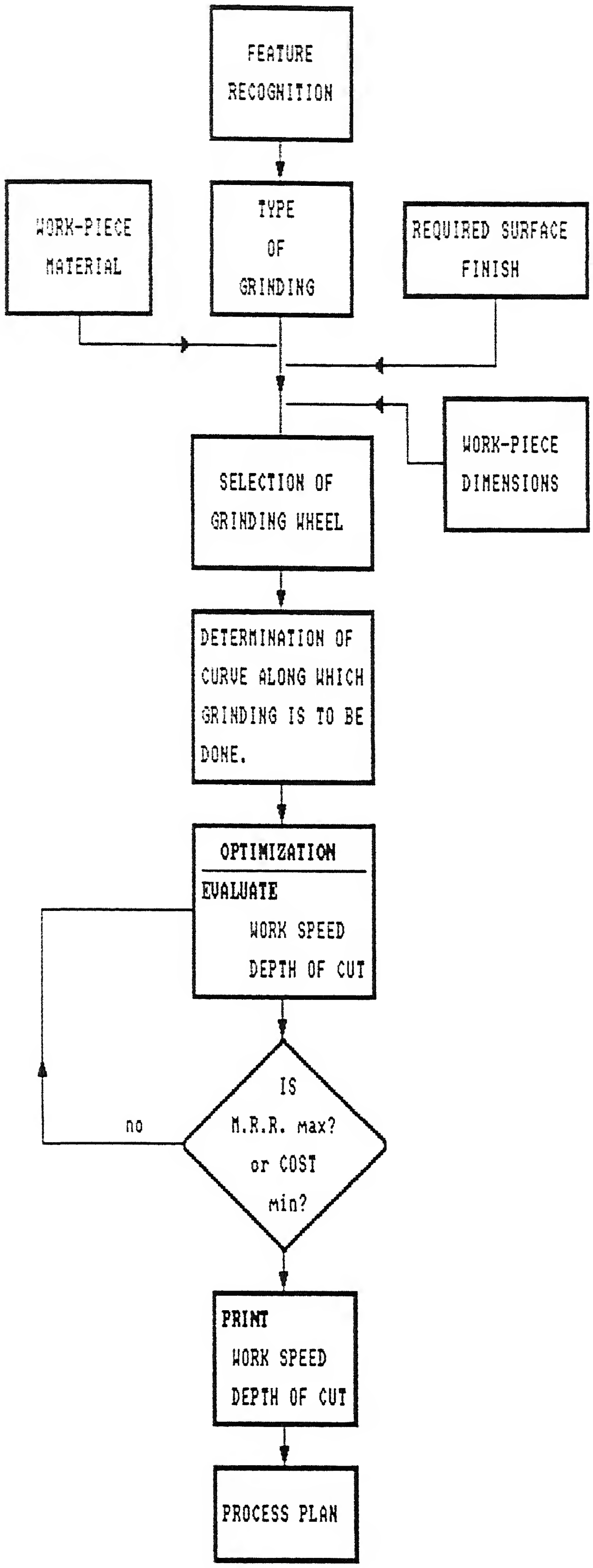


Figure 3.1: System flow chart for the proposed CAPP system for fine grinding.

- by primitives,
- by AutoCAD.

In the first method "by coordinates", the coordinates for various points on workpiece surfaces are entered to define the workpiece geometry. In the second method "by primitives" method, the user provides the details about the workpiece surface in terms of the primitives of the features in certain sequence and the system synthesizes and recognizes the feature. In the third method by AutoCAD, the workpiece geometry is entered by AutoCAD. In the present work, primitive method is used for feature recognition.

Primarily, a workpiece can be divided into either a prismatic or axisymmetric type. For every surface to be ground, input is asked about the features and certain additional information about the features on it. For the case of prismatic workpiece, surface can be plane, curved, or plane and curved combined. Further, a plane surface can either have holes or no holes as additional features. In case of curved surface or curved portion of plane and curved surface, there are six choices: concave, convex, concave with holes, convex with holes, concave and convex combined, or concave and convex combined with holes. For axisymmetric workpiece, two options are there: either with holes or without holes. Figure 3.2 shows the primitives for feature recognition. Required dimensions on the part are also provided by the user. User also provides the required surface finish on each of the surfaces.

Based on these information, features are recognized on the workpiece surfaces. Further using the logic as displayed in Table 3.1, the type of grinding process required is decided, which can be surface, external cylindrical, internal cylindrical or centreless type of grinding. There is no clear demarcation between the range of usage of external cylindrical grinding process and centreless grinding process. However, based on various data books and machine specifications, system has used the workpiece dimension range for centreless grinding as given in Table 3.1. The present work has considered the case of only throughfeed type of grinding.

In case of curved surfaces, system is designed such that after determining the

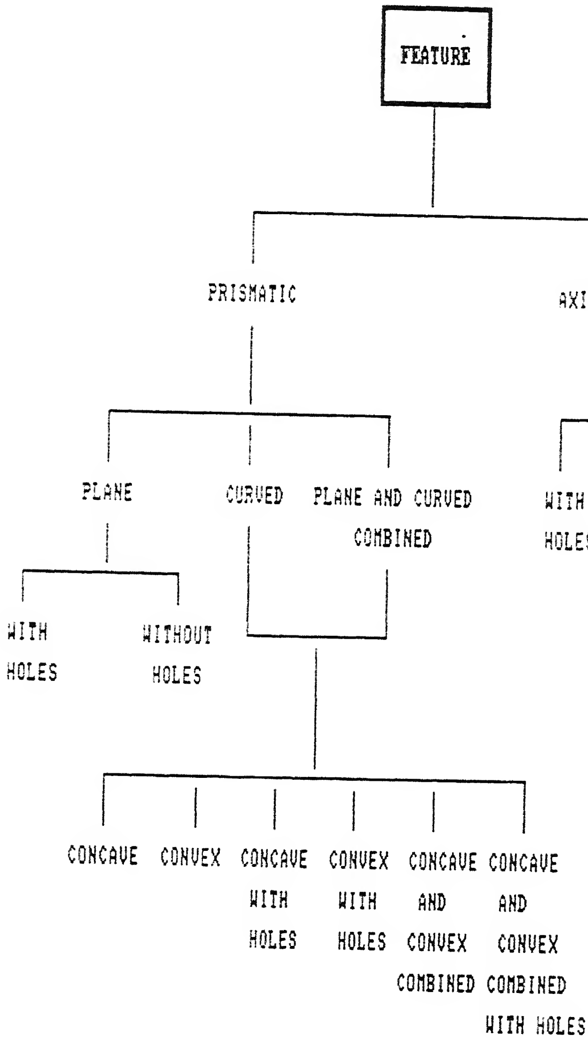


Figure 3.2: Primitives for feature recognition

Table 3.1: Decision Table for selection of type of grinding process.

Type of feature	Type of grinding process
Prismatic Workpiece	
1. Plane surface:	
with holes	Surface grinding for plane surface, Internal cylindrical grinding for holes.
without holes	Surface grinding for plane surface
2. Curved surface:	
Concave $(h_1 < \frac{l_1}{2})$	Surface grinding for concave surface*.
$(h_1 > \frac{l_1}{2})$	Internal cylindrical grinding for concave surface.
Convex $(h_2 < \frac{l_2}{2})$	Surface grinding for convex surface*.
$(h_2 > \frac{l_2}{2})$	External cylindrical grinding for convex surface.
Concave with holes	Same as for concave surface, with internal cylindrical grinding for holes.
Convex with holes	Same as for convex surface, with internal cylindrical grinding for holes.
Concave and convex combined	Same as for combination of concave and convex surfaces.
Concave and convex combined with holes	Same as for combination of concave and convex surfaces, with internal cylindrical grinding for holes.
3. Plane and curved combined	Surface grinding for plane portion, other processes same as for curved surfaces.
Axisymmetric Workpiece	
without holes	
(3<(m/n)>8),m<10,n<2	Centreless grinding for cylindrical surface.
otherwise	External cylindrical grinding for cylindrical surface.
with holes	same as above, with internal cylindrical grinding for holes.

where h_1 = the depth of concave surface, l_1 = the length of spread of concave surface, h_2 = the height of concave surface, l_2 = the length of spread of convex surface, m = the length of cylindrical workpiece. n = the radius of cylindrical workpiece.

* For concave and convex surfaces, internal and external cylindrical grinding are usually recommended. However with suitable adjustments of grinding wheel spindle, surface grinding can be used for some cases.

type of grinding required, it gives the equation of the curve along which grinding has to be done. The left hand corner of the surface is taken as the origin.

Figure 3.3 shows the flow chart for feature recognition module.

3.2 Workpiece Material

In this module, a list of materials is provided to the user and he has to select the workpiece material by entering the code for the material.

The list of materials provided to the user is:

- Alloys
- Alnico
- Aluminium
- Brass
- Bronze
- Cast iron
- Copper
- Monel metal
- Nimonic
- Steel
- Tungsten carbide.

The subclasses for the above materials can be seen from Appendix B. If the workpiece material is not found in the list provided, the program for workpiece material module can be suitably modified to add the material to the original list.

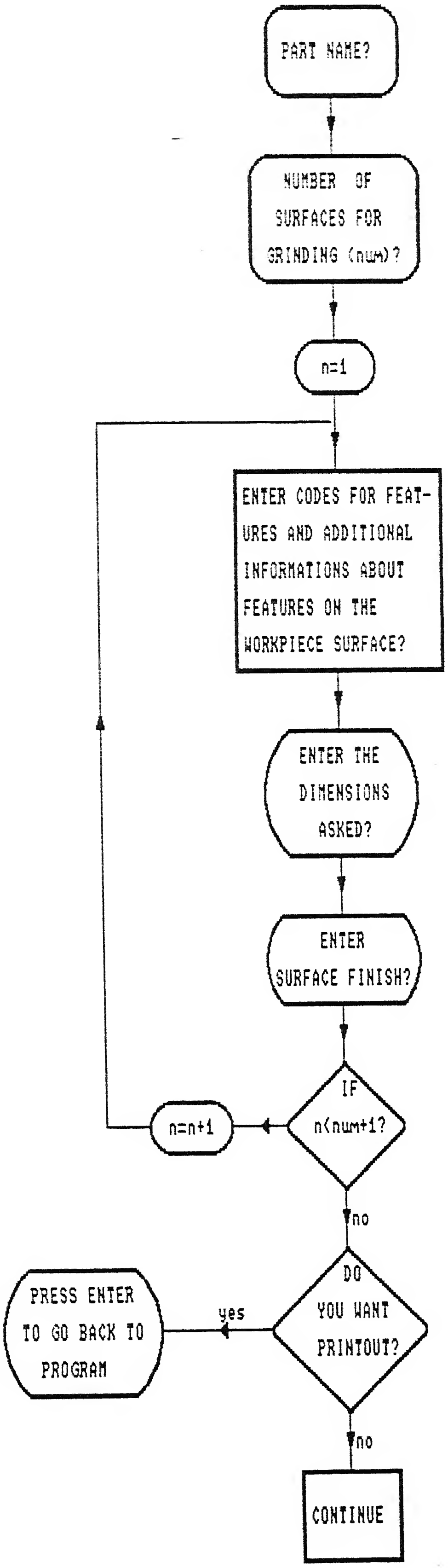


Figure 3.3: Flow chart for feature recognition module.

3.3 Grinding Wheel Selection

As discussed in the previous chapter, grinding wheel specification consists of:

- Abrasive type
- Grit size
- Wheel grade
- Wheel structure
- Bond type

The basic requirements of an abrasive are:

1. It should be harder than the material it is to abrade.
2. It should have high toughness. High toughness implies that an abrasive grain is less likely to fracture or fragment each time it engages or impacts the workpiece.
3. It should be friable enough to regenerate sharp cutting edges (self-sharpen) as the grain dulls by attrition during use.

Abrasive material selection depends on the workpiece properties like hardness and tensile strength.

Factors responsible for grit size selection are material removal rate and surface finish required on the workpiece surface. Coarse grits are used for soft or ductile materials. Harder and brittle materials require fine grits. For precision grinding, fine grits are used. With large size grits, material removal rate is high and surface finish obtained is less. Following table (Table 3.2) shows the grit size used for various ranges of surface finish.

Wheel grade or hardness provides a general indication of wheel strength and degree to which abrasive grains are tightly held by the binder. Its selection depends on the hardness of the workpiece material. Soft wheels are used for harder

Table 3.2: Grit size for various range of surface finish

Surface finish range(microns)	Grit size
less than 0.05	220
0.05 - 0.2	150
0.2 - 0.4	80
0.4 - 0.6	60
0.6 - 0.8	54
greater than 0.8	46

materials and vice versa. For rough grinding, medium to hard grade wheel is used whereas soft wheels are used for precision grinding.

Wheel structure number indicates the volumetric concentration of abrasive grains in the wheel. Concentration of abrasive grains, bond material and pores can be altered to control the wheel structure and grade. Its selection depends on hardness and ductility of the workpiece material. For ductile materials, open structure is used whereas a dense structure is required for hard and brittle materials.

Bond material must be strong enough to withstand grinding forces, temperatures and centrifugal forces without disintegrating. It should also resist chemical attack by fluid.

In the present work, selection of grinding wheel is based on various database, and data from industrial experience since mathematical models relating grinding wheel parameters are not available. The data bases are taken from New American Machinists' handbook (Le Grand, 1955), The grinding wheel (Lewis, 1959), and Machining data handbook. The final database which the system has used is given in Appendix B. Grit size is selected on the basis of the surface finish required on the workpiece surfaces. Therefore space has been left in its place in the grinding wheel specification as shown in Appendix B.

3.4 Determination of Operating Parameters

Operating parameters like work speed and depth of cut can be determined by optimizing material removal rate or total grinding cost. Material removal rate has to be maximized and grinding cost has to be minimized. As discussed in the previous chapter, the main constraints are on cutting forces or on power, surface finish required and temperature attained during the operation. In the present case, optimization method has been applied for surface grinding and external cylindrical grinding. Due to non-availability of data and mathematical relations, same could not be applied to other grinding methods. For surface grinding, mathematical relation for total cost was available. As cost relation was not available for external cylindrical grinding, we have used relation for material rate as objective function. The various relations used are:

1. Total Cost (per unit stock removal)

$$z' = \frac{A'}{v.d} + \frac{C'}{V_1}\left(\frac{V}{v.d}\right)^{\nu} \tag{3.1}$$

where z' = the total cost per unit stock removal.

A' = the man-machine cost per unit wheel width.

v = the table speed.

d = the depth of cut.

C' = the dressing cost per cycle per unit wheel width.

V_1 = the constant depending on wheel-workpiece combination.

V = the grinding wheel speed (assumed to be constant).

ν = the exponent relating wheel life with equivalent grinding thickness.

2. Material Removal Rate (per unit wheel width)

$$z = v.d \tag{3.2}$$

where z = the material removal rate per unit wheel width.

3. Tangential Force (per unit wheel width)

$$F_t = F_1(\frac{v.d}{V})^f \tag{3.3}$$

where F_t = the tangential grinding force per unit wheel width.

F_1 = the reference tangential force for unit equivalent chip thickness.

f = the exponent relating grinding force and equivalent grinding thickness.

4. Surface Roughness

$$R = R_1(\frac{v.d}{V})^r \tag{3.4}$$

where R = the surface roughness.

R_1 = the reference surface roughness.

r = the exponent relating surface roughness with equivalent grinding thickness.

5. Mean Temperature (for a unit width of wheel-work contact)

$$\theta = 0.754.\frac{u.v^{0.5}.d^{0.75}}{(\sqrt{D_e}(k\rho c)_w)^{0.5}} \tag{3.5}$$

where θ = the mean temperature for a unit width of wheel-work contact.

u = the specific grinding energy.

D_e = the equivalent diameter.

k = the thermal conductivity of the workpiece material.

ρ = the density of the workpiece material.

c = the specific heat of workpiece material.

6. Power Required for Grinding

$$P = 13.8v.d + 0.001V + (C_1 + C_2.\frac{v}{V.D_e})D_e^{0.5}.d^{0.5}.0.06 \tag{3.6}$$

where P = the power required for grinding.

$C_1 = 7.55 \times 10^{-3}$ and $C_2 = 2.1 \times 10^{-3}$ (Malkin and Koren, 1980)

Value of A'=0.0029 cost units/sec/mm, and that of C'=1.14 cost units/mm (Snoeys and Peters, 1974). Values of V_1 and ν in equation (3.1) are obtained from grinding charts given in Appendix A (Snoeys and Peters, 1974). Values of F_1, R_1, f, r, u in equations (3.3), (3.4) and (3.5) are also obtained from the grinding charts.

(1). Surface Grinding Optimization

From equations (3.1), (3.3), (3.4), and (3.5) for surface grinding, the optimization problem can be written as follows. The decision variables are table speed v, and depth of cut d.

Minimize $z' = \frac{A'}{v.d} + \frac{C'}{V_1} \left(\frac{V}{v.d}\right)^{\nu}$ (minimization of total cost)

subject to

$F_1 \left(\frac{v.d}{V}\right)^f \leq F_{max}$; (constraint on tangential force)

$R_1 \left(\frac{v.d}{V}\right)^r \leq R_{max}$; (constraint on surface roughness)

$0.754. \frac{u.v^{0.5}.d^{0.75}}{(\sqrt{D_e}(k\rho c)_w)^{0.5}} \leq \theta_{max}$. (constraint on mean temperature)

Value of F_{max} used is 5 N based on experimental values. Value of R_{max} is given by the surface finish required on the workpiece. Value of θ_{max} is limited by the workpiece burn. Based on the metallurgical considerations, value used by the system = 800 K.

(2). External Cylindrical Grinding Optimization

From equations (3.2), (3.6), (3.4), and (3.5), the optimization problem for external cylindrical grinding can be written as follows. The decision variables are

peripheral speed v, and depth of cut d.

Maximize z = v.d (maximization of material removal rate)

subject to

$$13.8v.d + 0.001V + (C_1 + C_2.\frac{v}{V.D_e})D_e^{0.5}.d^{0.5}.0.06 \leq P_{max};$$

(constraint on total power)

$$R_1(\frac{v.d}{V})^r \leq R_{max};$$ (constraint on roughness value)

$$0.754.\frac{u.v^{0.5}.d^{0.75}}{(\sqrt{D_e}(k\rho c)_w)^{0.5}} \leq \theta_{max}.$$ (constraint on mean temperature)

Value for P_{max} is taken from the specifications of grinding machine in Manufacturing science lab. as 3 H.P. The values of R_{max} and θ_{max} are taken same as in first optimization problem.

Results of all the modules are stored in various files for use at a later stage. User has to give the name of the files in which results of feature recognition module and workpiece material module for running the module of optimization.

3.5 Solution Methodology - Genetic Algorithms

The above discussed optimization problem for the grinding model has been solved using genetic algorithm technique (GA).

GA works on a population of points instead of a single point. Therefore, GAs are likely to find the global solutions. It uses probabilistic transition rules instead of deterministic transition rules. This reduces the bias in search. Initially the search is random and as iteration progresses, GAs obtain a directed search adaptively. It consists of three operations: reproduction, cross-over, and mutation.

Reproduction operator selects good strings from a population. Better strings get more number of copies. Cross-over operator exchanges information between two strings selected at random. Children strings are produced by exchanging

information between two parent strings. Mutation operator alters a bit value to another with a small probability.

Various GA parameters used are:

Number of generations = 200.

Population size = 100.

Cross Over probability = 1.0.

Mutation probability = 0.

Number of variables = 2.

Penalty coefficient = 4.0

Convergence and closeness epsilons = 0.001.

The values for number of generations, population size, convergence and closeness epsilons, and penalty coefficient were taken on the basis of hit and trial method to get better results. Mutation operator has not been used in the system. Therefore value for mutation probability is taken as zero.

In case of constrained optimization, objective function f(x) is replaced by the penalized function:

$$F(x,y) = f(x,y) + \sum_{j=1}^{J} u_j < g_j(x,y) >^2 \tag{3.7}$$

where J is the number of constraints, u_j is the penalty coefficient, $g_j(x,y)$ is the constraint function, f(x,y) is the objective function, and F(x,y) is the penalized function. Value for u_j is taken as 4.0 for all the constraints although it can be varied.

In the present case, penalized function can be written as:

$$F(v,d) = f(v,d) + \sum_{j=1}^{J} u_j < g_j(v,d) >^2 \tag{3.8}$$

For first optimization problem for surface grinding,

$$\begin{aligned} f(v,d) &= z' \\ g_1(v,d) &= \tfrac{F_1}{F_{max}}(\tfrac{v.d}{V})^f - 1.0 \\ g_2(v,d) &= \tfrac{R_1}{R_{max}}(\tfrac{v.d}{V})^f - 1.0 \end{aligned}$$

$$g_3(v.d) = 0.754.\frac{u.v^{0.5}.d^{0.75}}{(\sqrt{D_e}(k\rho c)_w)^{0.5}.\theta_{max}} \text{ -1.0}$$

For second optimization problem for external cylindrical grinding,

$$\begin{aligned}
f(v,d) &= z \\
g_1(v,d) &= \frac{1}{P_{max}}.[13.8v.d+0.001V+(C_1+C_2.\frac{v}{V.D_e})D_e^{0.5}.d^{0.5}.0.06]\text{-1.0} \\
g_2(v,d) &= \frac{R_1}{R_{max}}(\frac{v.d}{V})^f\text{-1.0} \\
g_3(v,d) &= 0.754.\frac{u.v^{0.5}.d^{0.75}}{(\sqrt{D_e}(k\rho c)_w)^{0.5}.\theta_{max}} \text{ -1.0}
\end{aligned}$$

Genetic algorithm is applied to this penalized function (Deb, 1995). The program for genetic algorithm is taken from work of Agrawal (Agrawal, 1995). It has been suitably modified to suit the present problem.

These optimization techniques are implemented using Borland C++ compiler.

Chapter 4

IMPLEMENTATION AND RESULTS

In the previous chapters, an overview of fundamentals of grinding wheel and their influence on the selection of grinding wheel, and formulation of non-linear optimization problem for solving for optimal cutting conditions has been presented.

The present software has been developed in two parts: one is feature recognition for deciding the type of grinding process and knowledge base development for selecting grinding wheel and the other part deals with optimization program to determine grinding conditions optimally. Both are implemented using Borland C++ compiler. Because of size of program, a single project file could not be made combining both the parts. Therefore, both parts has to be run separately on a IBM compatible PC-AT/XT computer.

The flow of data in the present system is given in Figure 3.1.

4.1 Inputs to the System

The program needs input in the form of:

1. Features on the workpiece surface.

2. Required surface finish.

3. Workpiece dimensions.

4. Workpiece material.

User should give input in the order in which it is asked. Figure 3.2 shows the order of input of data for feature recognition module. Results for test examples are given at the end of the chapter. Checks and error messages are incorporated at all the places where input is not appropriate.

4.2 System files

There are two project files in the system:

1. main.prj
2. opti.prj

First project file main.prj contains 18 files. These are:

`main.c`	It is the main file.
`recall.c`	gives choices about the selection of modules.
`call.c`	gives options about the features on the workpiece surface.
`check_1.c`	contains options of additional information about features on plane surface.
`check_2.c`	contains options of additional information about features on curved surface.
`check_22.c`	contains options of additional information about features on axisymmetric surface.
`dum.c`	contains miscellaneous functions.
`file.c`	works when some of the modules are skipped and program runs on earlier information.
`file1.c`	works when some of the modules are skipped and program runs on earlier information.
`material.c`	contains information about the workpiece material.
`menu.c`	contains miscellaneous functions.
`sel_n.c`	carries out the selection of grinding wheel.

`s_n.c`	`carries out the selection of grinding wheel.`
`s_n1.c`	`carries out the selection of grinding wheel.`
`result_f.c`	`processes the information from feature recognition module for prismatic workpiece.`
`r2_f.c`	`processes the information from feature recognition module for prismatic workpiece.`
`r3_f.c`	`processes the information from feature recognition module for prismatic workpiece.`
`res_f.c`	`processes the information from feature recognition module for axisymmetric workpiece.`

Second project file opti.prj contains three files. These are:

`opti.c`	`It is the main program.`
`sur.c`	`does optimization for surface grinding.`
`cyl.c`	`does optimization for cylindrical grinding.`

Apart from these files, there is one header file "recog.h".

In the project file main.prj, main file is main.c which calls the function "recall" from file recall.c. File recall.c calls the functions "call" from file call.c, "alt1 and alt2" from file.c. Functions "list1" from check_1.c, "list2 and list3" from check 2.c, "list4" from check_22.c, "material" from material.c, "result" from result_f.c, "result6, print1 and print2" from res_f.c are called in file call.c. Functions "result" from file result_f.c, "result6, print1 and print2" from res_f.c, "material" from material.c, "rak1, rak2 and m_rt" from file1.c are called in file file1.c. File result_f.c calls the functions "select" from file sel_n.c , "result2" from r2_f.c, "result3" from r3_f.c and "equation" from res_f.c. Functions "select1" from s_n.c and "select2" from s_n1.c are called in file sel_n.c. Miscellaneous functions from file menu.c are called in a number of files. Figure 4.1 shows the inter-relationship of various files of main.prj.

In the project file opti.prj, main file is opti.c which calls the functions "main_ga" from file sur.c and "main_cga" from file cyl.c. Figure 4.2 shows the inter-relationship of files of opti.prj.

4.3 Results

Test examples for workpiece shown in Figure 4.3(a), Figure 4.3(b) is given at the end of the chapter followed by the files containing results of all the modules. The grinding wheel speed is kept at 30 m/sec for both the examples. Figure 4.4, Figure 4.5, and Figure 4.6 show the variation of table speed and depth of cut with surface finish for various steels for surface grinding. Figure 4.7, Figure 4.8, and Figure 4.9 show the variation of peripheral speed and depth of cut with surface finish for various steels for external cylindrical grinding.

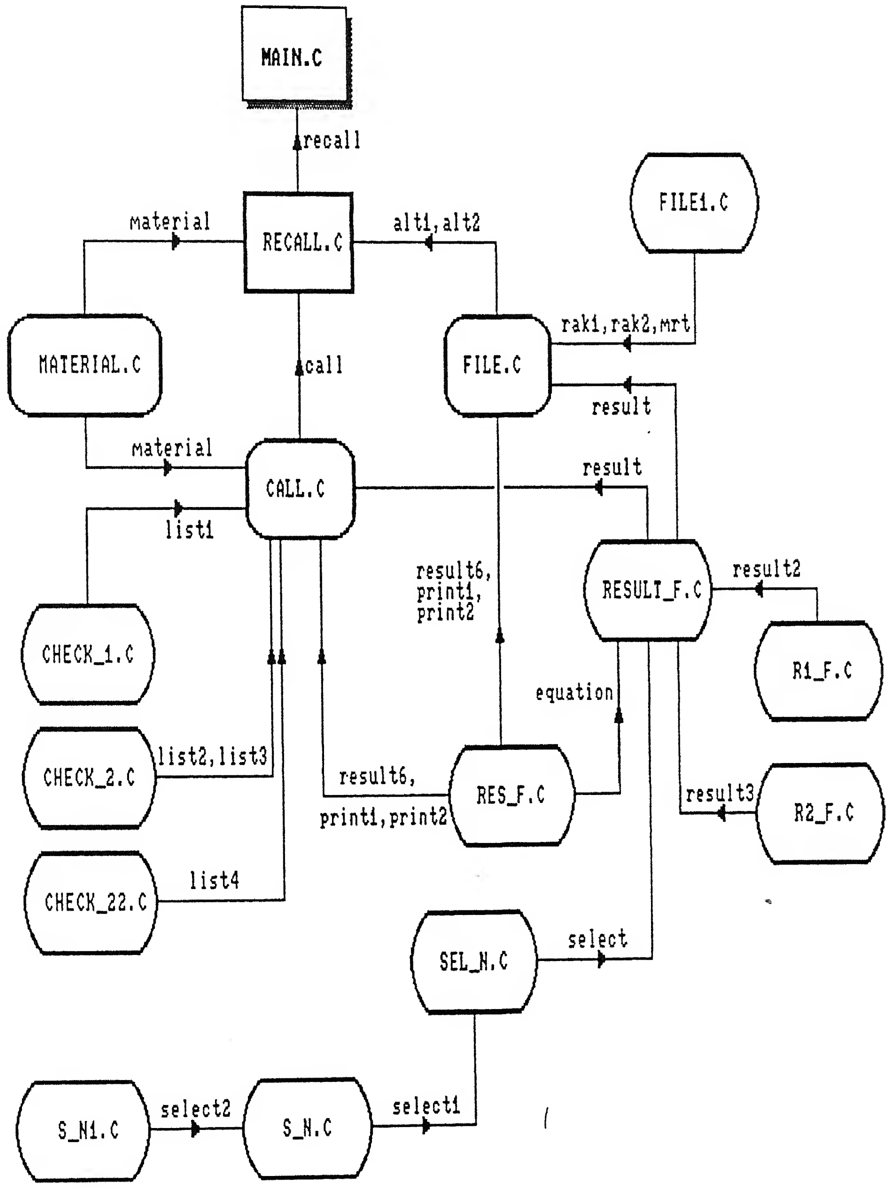


Figure 4.1: Inter-relationship of files in project file main.prj

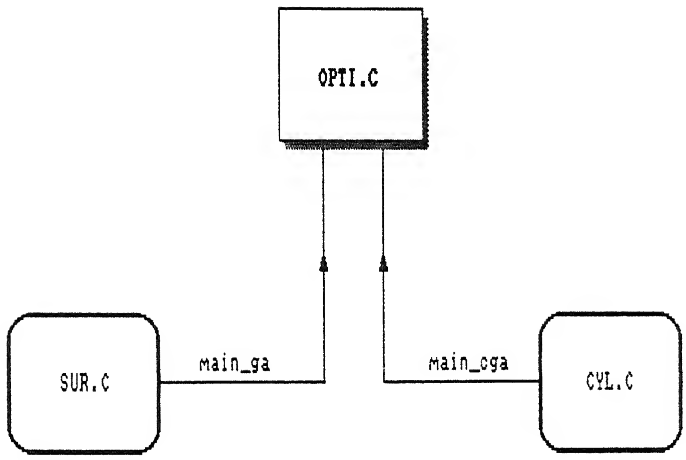
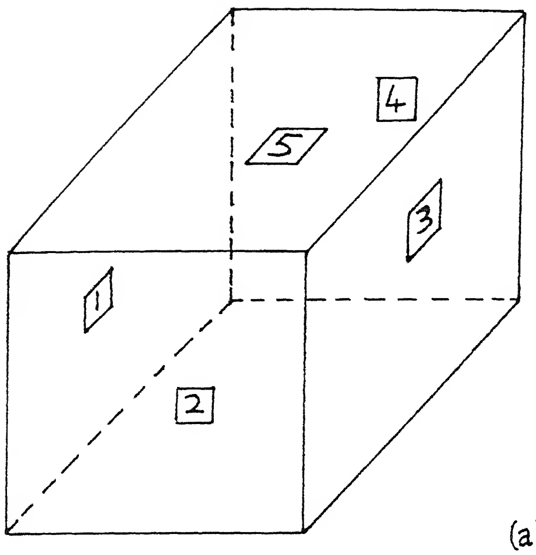
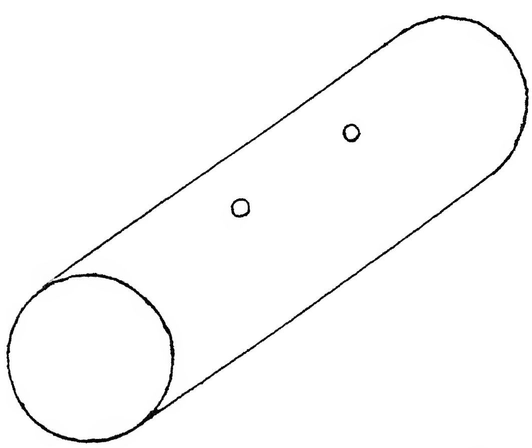


Figure 4.2: Inter-relationship of files in project file opti.prj



(a)

Surface 1: Plane with holes.
Surface 2: Convex surface with hole.
Surface 3: Concave and convex surfaces combined.
Surface 4: Plane without holes.
Surface 5: Concave surface with plane portion.



(b)

Holes on cylindrical surface.

Figure 4.3: Drawing of sample parts (a) Prismatic (b) Axi-symmetric

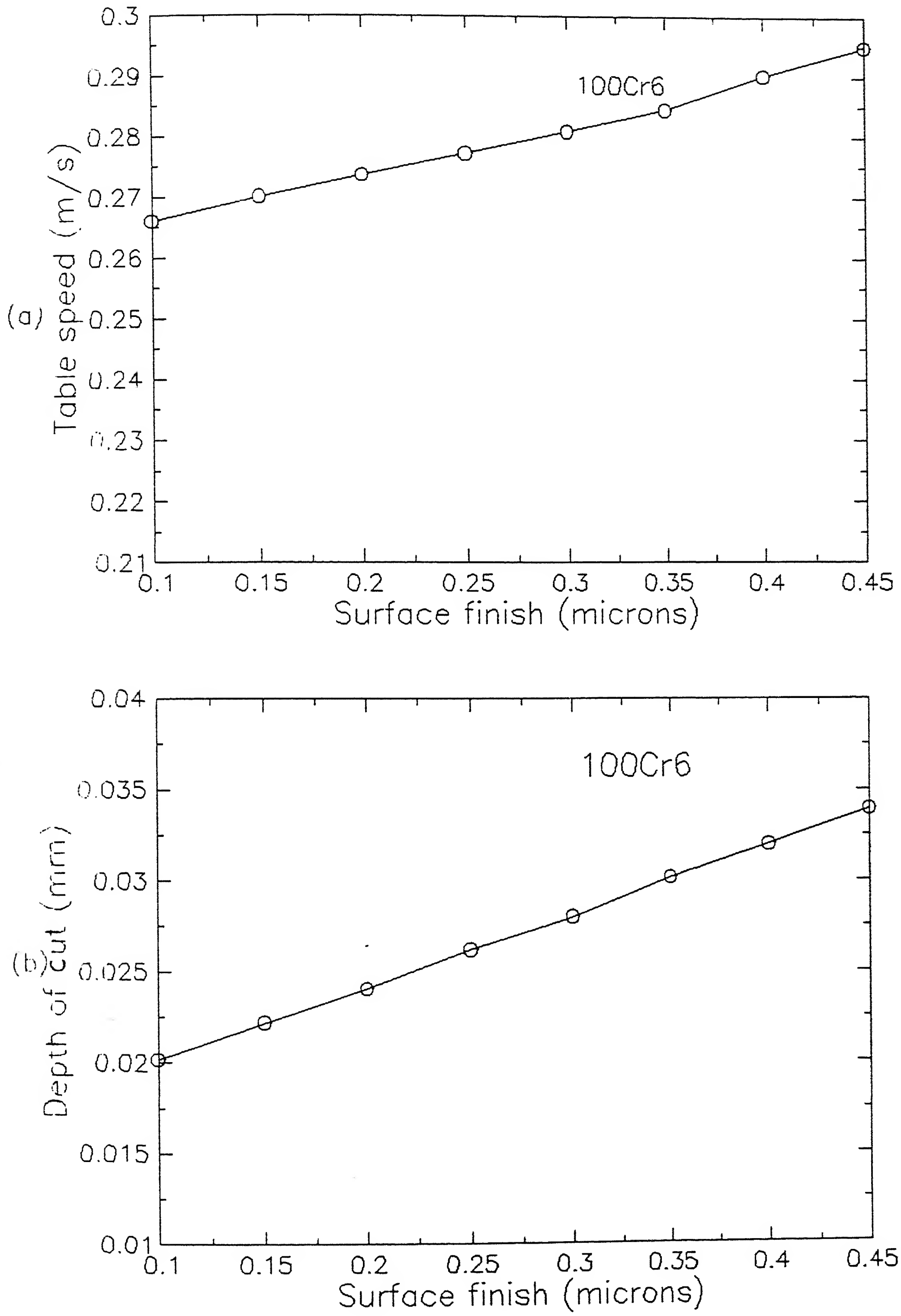


Figure 4.4: Variation with surface finish for 100Cr6 steel for surface grinding of (a) Table speed (b) Depth of cut

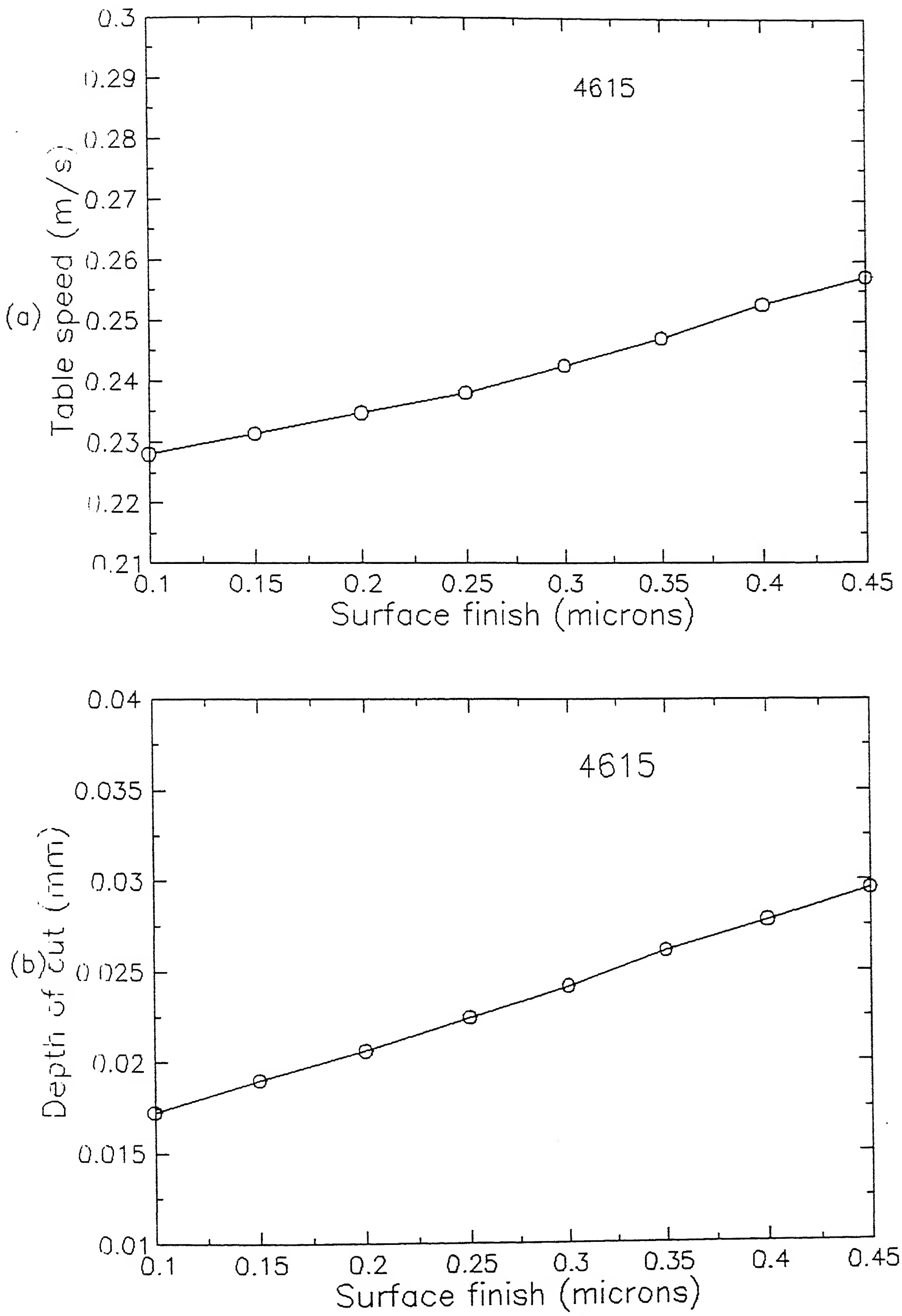
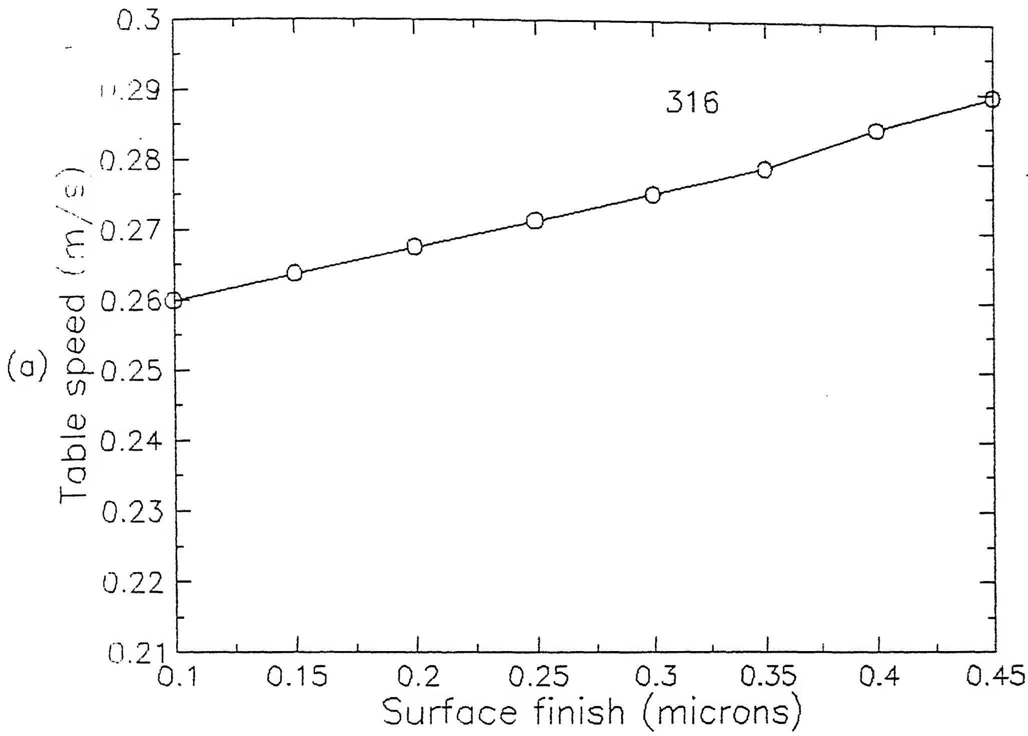


Figure 4.5: Variation with surface finish for 4615 steel for surface grinding of (a) Table speed (b) Depth of cut



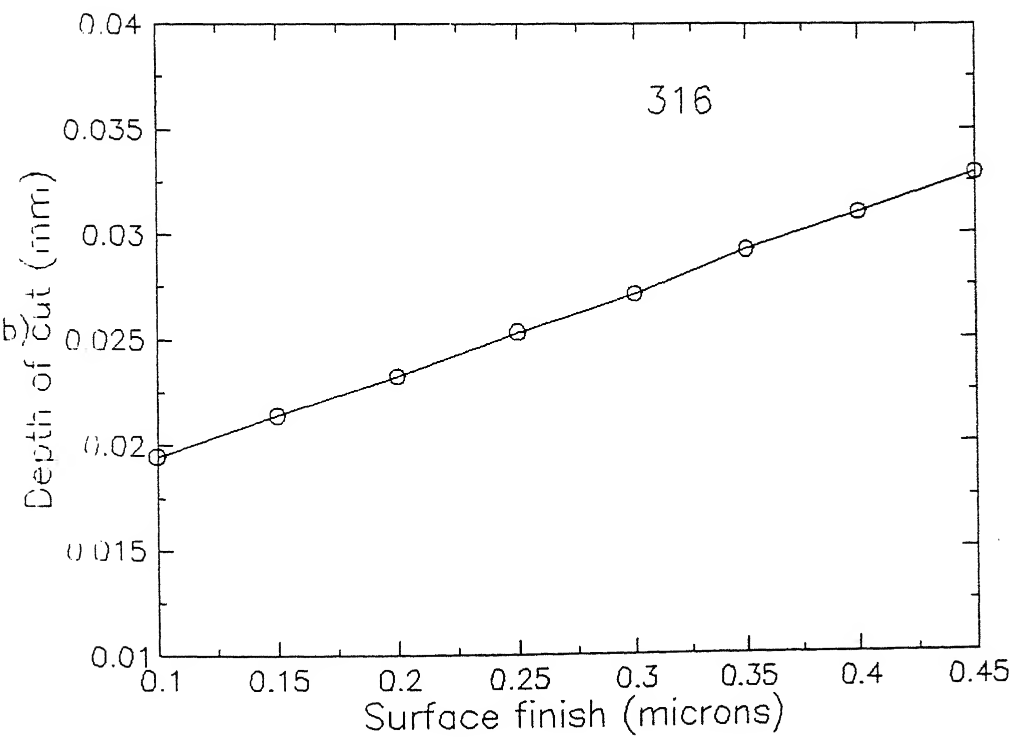


Figure 4.6: Variation with surface finish for 316 steel for surface grinding of (a) Table speed (b) Depth of cut

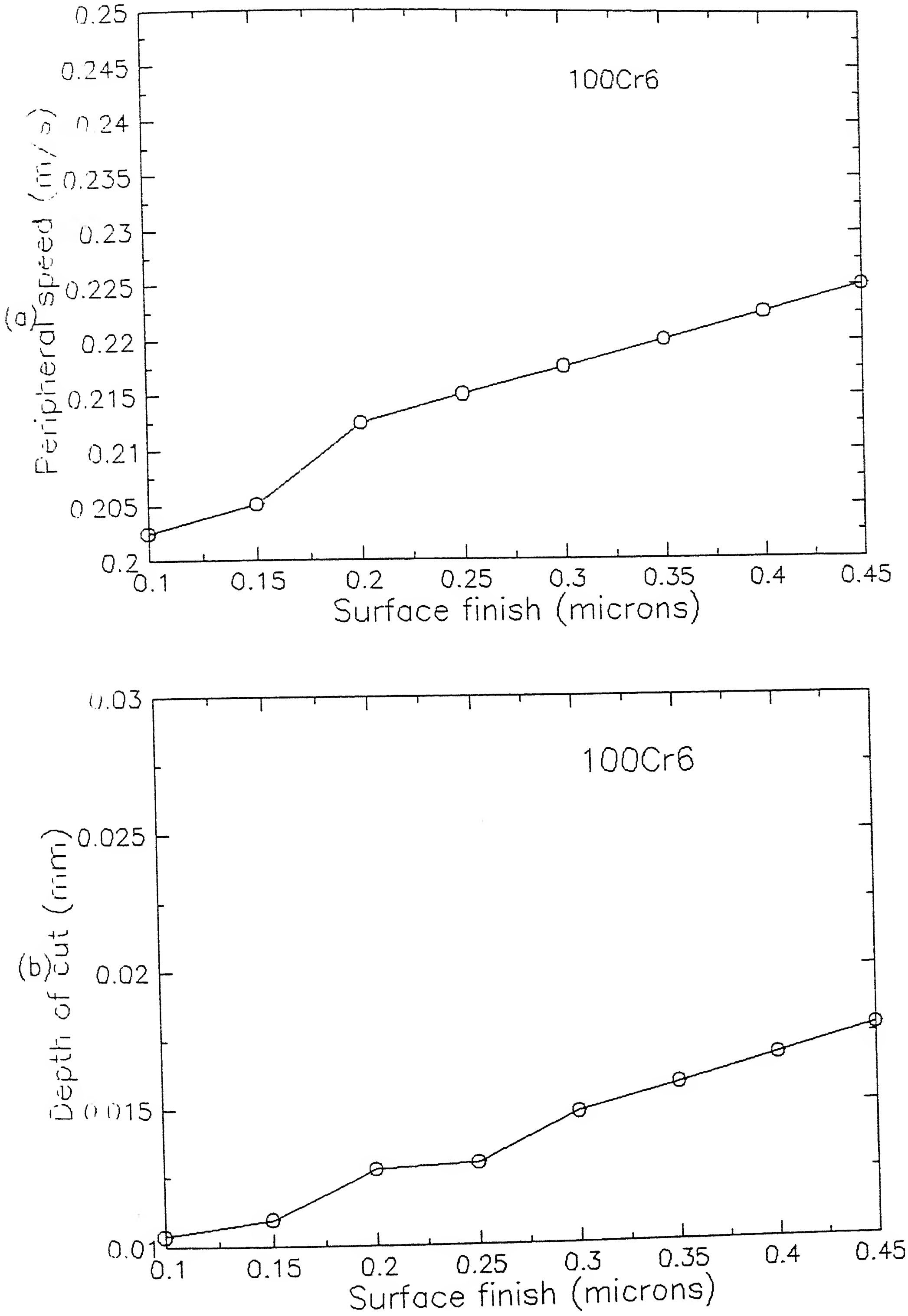
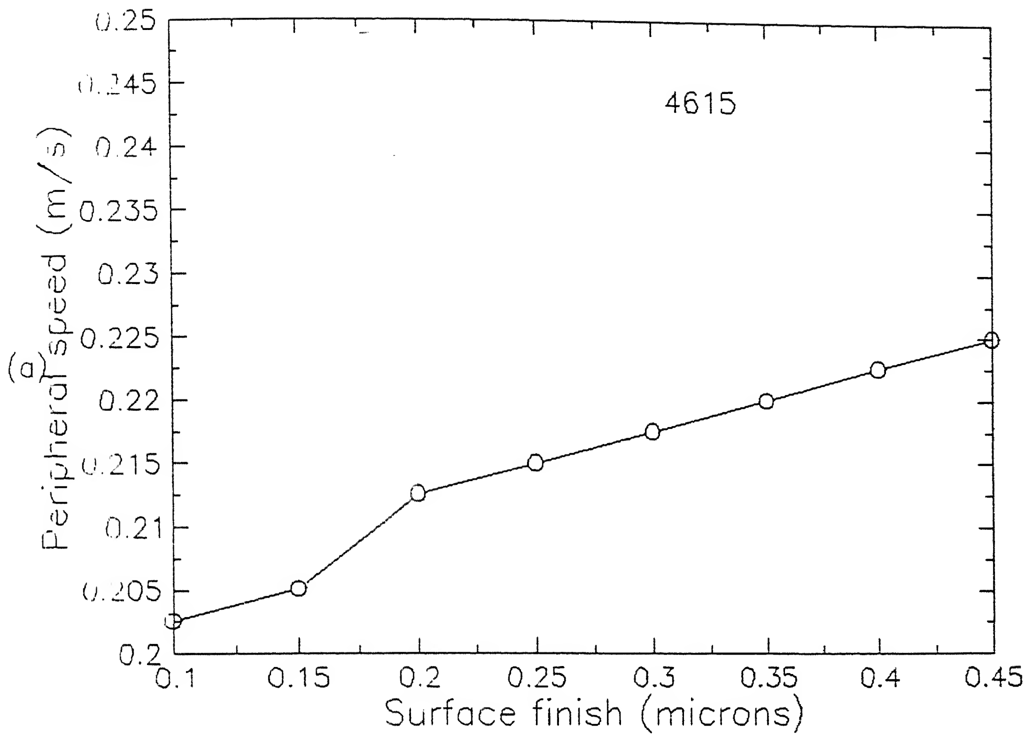


Figure 4.7: Variation with surface finish for 100Cr6 steel for external cylindrical grinding of (a) Peripheral speed (b) Depth of cut



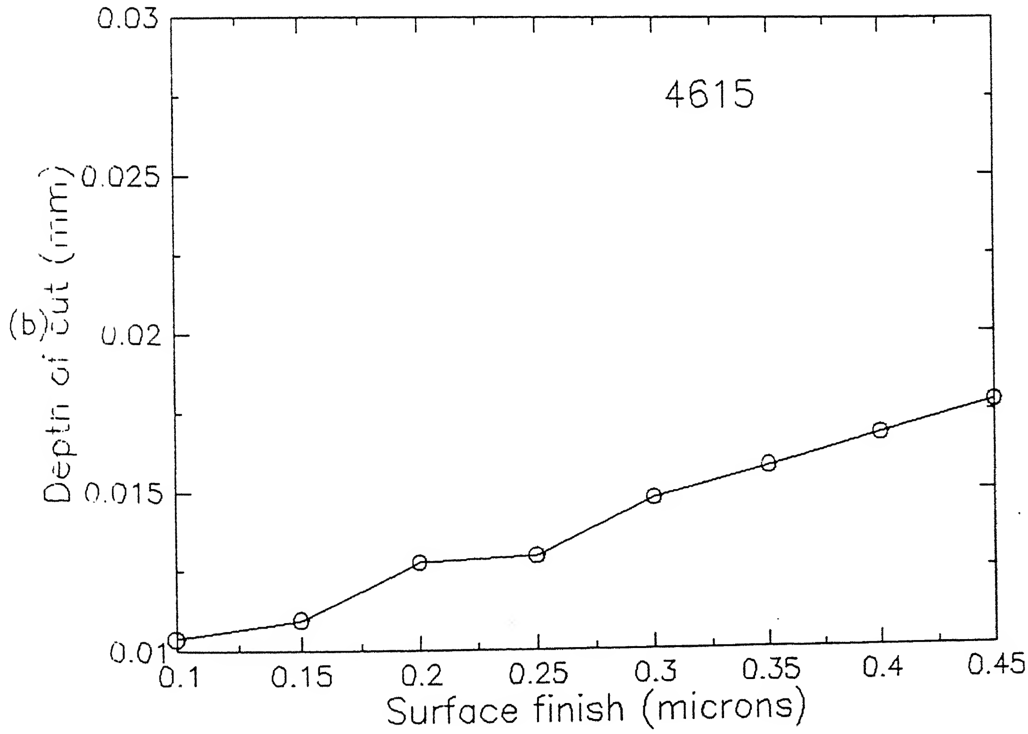


Figure 4.8: Variation with surface finish for 4615 steel for external cylindrical grinding of (a) Peripheral speed (b) Depth of cut

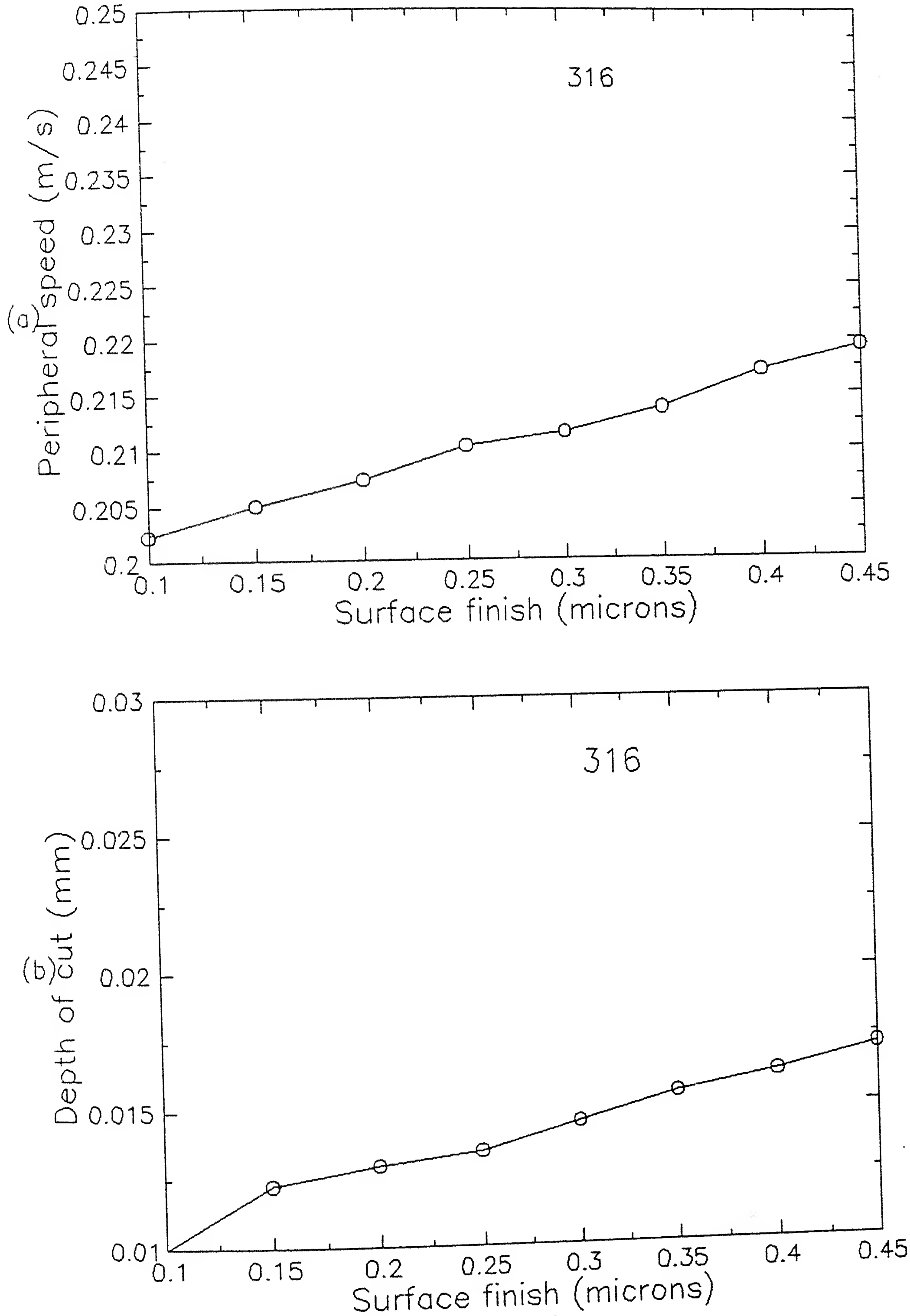


Figure 4.9: Variation with surface finish for 316 steel for external cylindrical grinding of (a) Peripheral speed (b) Depth of cut

TEST EXAMPLE NO. 1

PRISMATIC WORKPIECE

COMPUTER - AIDED PROCESS PLANNING

OF FINE GRINDING

by

RAJESH KUMAR BURMAN

```
CAPP FOR FINE GRINDING


          èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
          ¤ 1. FEATURE RECOGNITION                   ¤
          ¤ 2. WORKPIECE MATERIAL                    ¤
          ¤ 3. GRINDING WHEEL SELECTION              ¤
          ¤ 4. OPTIMIZATION OF GRINDING PARAMETERS ¤
          ¤ 5. OUTPUTS                               ¤
          ¤ 6. EXIT                                  ¤
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 Enter the selection:1
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 CAPP FOR FINE GRINDING

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             ¤          FEATURE RECOGNITION          ¤
             ¤ !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! ¤
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                   ¤ 1. NEW PART        ¤
                   ¤ 2. EXISTING PART ¤
                   ¤ 3. EXIT            ¤
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  Enter the selection:1
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¤*************************************************************¤
¤*    THIS MODULE RECEIVES THE INPUTS REGARDING THE TYPE     *¤
¤*    OF PART, TYPE OF SURFACE, ADDITIONAL GEOMETRICAL       *¤
¤*    INFORMATION AND THE SURFACE FINISH REQUIRED.            *¤
¤*************************************************************¤
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CAPP OF FINE GRINDING                                   FEATURE RECOGNITION

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¤*******************************************************¤
¤           FEATURES FOR THE WORKPIECE SURFACES          ¤
¤*******************************************************¤
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      èëëëëëëëëëëëëëëëëëë£
      ¤ TYPE OF PART:- ¤
      àëëëëëëëëëëëëëëëëëë¥

              èëëëëëëëëëëëëëëëëëëëëëëëëëëë£
              ¤     1. PRISMATIC PART      ¤
              ¤     2. AXI-SYMMETRIC PART  ¤
              ¤     3. EXIT                ¤
              àëëëëëëëëëëëëëëëëëëëëëëëëëëë¥
 PART NAME(max 10 letters) : test
 Enter the feature code :1
 Please note:    MAX. NO. OF SURFACES FOR GRINDING
                 5 for TRIANGULAR
                 6 for RECTANGULAR
                 8 for HEXAGONAL

 Enter the number of surfaces for grinding:5
```

```
CAPP OF FINE GRINDING                                    FEATURE RECOGNITION

èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
¤ ********************************************************** ¤
¤         ADDITIONAL  INFORMATION ABOUT THE SURFACES           ¤
¤ ********************************************************** ¤
àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

 For surface no. 1

                  èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
                  ¤     1.PLANE SURFACE              ¤
                  ¤     2.CURVED SURFACE             ¤
                  ¤     3.PLANE AND CURVED COMBINED  ¤
                  ¤     4.EXIT                       ¤
                  àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥


 Enter the type of surface: 1
```

```
CAPP OF FINE GRINDING                                    FEATURE RECOGNITION

        èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
        ¤ ############################################## ¤
        ¤       ADDITIONAL FEATURES OF PLANE SURFACE      ¤
        ¤ ############################################## ¤
        àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

 Surface no.1
                       èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
                       ¤    1.WITH HOLE                  ¤
                       ¤    2.WITHOUT HOLE               ¤
                       ¤    3.EXIT                       ¤
                       àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

 Enter the code for type of plane surface: 1

 Enter the surface finish required       : 0.2
```

```
CAPP OF FINE GRINDING                                  FEATURE RECOGNITION

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¤ ********************************************************** ¤
¤        ADDITIONAL INFORMATION ABOUT THE SURFACES          ¤
¤ ********************************************************** ¤
àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

 For surface no. 2

                 èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
                 ¤     1.PLANE SURFACE              ¤
                 ¤     2.CURVED SURFACE             ¤
                 ¤     3.PLANE AND CURVED COMBINED  ¤
                 ¤     4.EXIT                       ¤
                 àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥


 Enter the type of surface: 2
```

```
CAPP OF FINE GRINDING                                  FEATURE RECOGNITION

           èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
           ¤ &&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&& ¤
           ¤      ADDITIONAL FEATURES OF CURVED SURFACE        ¤
           ¤ &&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&& ¤
           àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

 Surface no.2 èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
              ¤     1.CONCAVE                           ¤
              ¤     2.CONVEX                            ¤
              ¤     3.CONCAVE WITH HOLE                 ¤
              ¤     4.CONVEX WITH HOLE                  ¤
              ¤     5.CONCAVE AND CONVEX COMBINED       ¤
              ¤     6.CONCAVE AND CONVEX  WITH HOLE     ¤
              ¤     7.EXIT                              ¤
              àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

 Enter the code for curved surface                    :4
 Enter max. height of curve from surface(in cm.)      :3.0
 Enter length of spread of convex portion(in cm.)     :5.0

 Enter the surface finish required         : 0.3
```

```
CAPP OF FINE GRINDING                                        FEATURE RECOGNITION

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¤ ******************************************************** ¤
¤           ADDITIONAL INFORMATION ABOUT THE SURFACES         ¤
¤ ******************************************************** ¤
àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

 For surface no. 3

                    èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
                    ¤     1.PLANE SURFACE               ¤
                    ¤     2.CURVED SURFACE              ¤
                    ¤     3.PLANE AND CURVED COMBINED   ¤
                    ¤     4.EXIT                        ¤
                    àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥


 Enter the type of surface: 2




CAPP OF FINE GRINDING                                        FEATURE RECOGNITION

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             ¤ &&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&& ¤
             ¤       ADDITIONAL FEATURES OF CURVED SURFACE        ¤
             ¤ &&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&& ¤
             àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

 Surface no.3 èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
              ¤     1.CONCAVE                              ¤
              ¤     2.CONVEX                               ¤
              ¤     3.CONCAVE WITH HOLE                    ¤
              ¤     4.CONVEX WITH HOLE                     ¤
              ¤     5.CONCAVE AND CONVEX COMBINED          ¤
              ¤     6.CONCAVE AND CONVEX  WITH HOLE        ¤
              ¤     7.EXIT                                 ¤
              àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

 Enter the code for curved surface                     :5
 Enter max.depth of concave curve from surface(in cm.):0.8
 Enter length of spread of concave portion(in cm.)     :3.0
 Enter max.height of convex curve from surface(in cm.):2.0
 Enter length of spread of convex portion(in cm.)      :4.0
 Which curve is first(1 for convex,2 for concave)      :1

 Enter the surface finish required        : 0.4
```

```
CAPP OF FINE GRINDING                                    FEATURE RECOGNITION

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¤ ********************************************************** ¤
¤         ADDITIONAL  INFORMATION ABOUT THE SURFACES         ¤
¤ ********************************************************** ¤
àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

 For surface no. 4

                 èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
                 ¤     1.PLANE SURFACE              ¤
                 ¤     2.CURVED SURFACE             ¤
                 ¤     3.PLANE AND CURVED COMBINED  ¤
                 ¤     4.EXIT                       ¤
                 àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

 Enter the type of surface: 1
```

```
CAPP OF FINE GRINDING                                    FEATURE RECOGNITION

       èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
       ¤ ############################################## ¤
       ¤      ADDITIONAL FEATURES OF PLANE SURFACE      ¤
       ¤ ############################################## ¤
       àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

 Surface no.4
                     èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
                     ¤    1.WITH HOLE                  ¤
                     ¤    2.WITHOUT HOLE               ¤
                     ¤    3.EXIT                       ¤
                     àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

 Enter the code for type of plane surface: 2

 Enter the surface finish required       : 0.3
```

```
CAPP OF FINE GRINDING                                    FEATURE RECOGNITION

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¤ ******************************************************** ¤
¤        ADDITIONAL INFORMATION ABOUT THE SURFACES          ¤
¤ ******************************************************** ¤
àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

For surface no. 5

              èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
              ¤     1.PLANE SURFACE              ¤
              ¤     2.CURVED SURFACE             ¤
              ¤     3.PLANE AND CURVED COMBINED  ¤
              ¤     4.EXIT                       ¤
              àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥


Enter the type of surface: 3


CAPP OF FINE GRINDING                                    FEATURE RECOGNITION

 èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
 ¤ @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@ ¤
 ¤  ADDITIONAL FEATURES FOR PLANE SURFACES WITH CURVED PORTIONS  ¤
 ¤ @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@ ¤
 àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥
Surface no.5
            èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
            ¤     1.CONCAVE                        ¤
            ¤     2.CONVEX                         ¤
            ¤     3.CONCAVE WITH HOLE              ¤
            ¤     4.CONVEX WITH HOLE               ¤
            ¤     5.CONCAVE AND CONVEX COMBINED    ¤
            ¤     6.CONCAVE AND CONVEX  WITH HOLE  ¤
            ¤     7.EXIT                           ¤
            àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

 Enter the surface code:1
 Enter max.depth of curve from surface(in cm.)      :3.0
 Enter length of spread of concave portion(in cm.):5.0
 Enter length of plane part(in cm.)                 :4.0
 Which is first(1 for plane,2 for concave)          :1

 Enter the surface finish required          : 0.4


          OUTPUTS OF FEATURE RECOGNITION MODULE SAVED IN ''test.fet'

Do you want to take the printout(y/n)
Enter 'y' or 'n'n
```

```
CAPP OF FINE GRINDING                                    WORKPIECE MATERIAL

   èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
   ¤ ***************************************************** ¤
   ¤   FOR THE MAJOR TYPE OF WORKPIECE MATERIAL SELECTED,  ¤
   ¤   FOLLOWING SUBCLASSES ARE AVAILABLE IN THE DATABASE  ¤
   ¤ ***************************************************** ¤
   àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

               èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
               ¤    a.HARDENED      STEEL        ¤
               ¤    b.SOFT          STEEL        ¤
               ¤    c.HIGH SPEED    STEEL        ¤
               ¤    d.PLAIN CARBON  STEEL        ¤
               ¤    e.ALLOY         STEEL        ¤
               ¤    f.NITRIDING     STEEL        ¤
               ¤    g.HIGH STRENGTH STEEL        ¤
               ¤    h.TOOL          STEEL        ¤
               ¤    i.CAST          STEEL        ¤
               ¤    j.NITRALLOY     STEEL        ¤
               ¤    k.STAINLESS     STEEL        ¤
               àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

Enter letter code for type of steel: k
```

```
CAPP OF FINE GRINDING                                    WORKPIECE MATERIAL

   èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
   ¤ ************************************************** ¤
   ¤   FOLLOWING MAJOR TYPES OF WORKPIECE MATERIALS     ¤
   ¤   ARE AVAILABLE IN THE DATABASE                    ¤
   ¤ ************************************************** ¤
   àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

               èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
               ¤    a.ALLOYS                     ¤
               ¤    b.ALNICO                     ¤
               ¤    c.ALUMINIUM                  ¤
               ¤    d.BRASS                      ¤
               ¤    e.BRONZE                     ¤
               ¤    f.CAST IRON                  ¤
               ¤    g.COPPER                     ¤
               ¤    h.MONEL METAL                ¤
               ¤    i.NIMONIC                    ¤
               ¤    j.STEEL                      ¤
               ¤    k.TUNGSTEN CARBIDE           ¤
               ¤    l.EXIT                       ¤
               àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥
Enter the letter code for workpiece material: j
```

CAPP OF FINE GRINDING WORKPIECE MATERIAL

```
èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
¤ ************************************************* ¤
¤   FOR THE MAJOR TYPE OF STEEL SELECTED, FOLLOWING  ¤
¤   SUBCLASSES ARE AVAILABLE IN THE DATABASE         ¤
¤ ************************************************* ¤
àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

         èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
         ¤  1.FREE MACHINING            ¤
         ¤  2.FERRITIC                  ¤
         ¤  3.AUSTENITIC                ¤
         ¤  4.MARTENSITIC               ¤
         ¤  5.PRECIPITATION HARDENING   ¤
         ¤  6.OTHERS                    ¤
         àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

Enter number code for type of stainless steel: 3




              WORKPIECE MATERIAL SAVED IN ''test.mat''

Do you want to take the printout (y/n):
 Enter 'y' or 'n'n
```

GRINDING WHEEL SELECTION

CAPP OF FINE GRINDING

èëë£
¤1. SURFACE GRINDING FOR PLANE PORTION AND INTERNAL GRINDING ¤
¤ FOR THE HOLE HAS TO BE DONE ON THE SURFACE NO. 1 ¤
àëëë¥

GRINDING WHEEL A 80 J 5 V WILL BE USED FOR INTERNAL CYLINDRICAL GRINDING

GRINDING WHEEL A 80 J 5 V WILL BE USED FOR SURFACE GRINDING

GRINDING WHEEL SELECTION

CAPP OF FINE GRINDING

èëëë£
¤2. EXTERNAL GRINDING FOR CONVEX SURFACE AND INTERNAL GRINDING ¤
¤ FOR HOLE HAS TO BE DONE ON SURFACE NO. : 2 ¤
àëëë¥

GRINDING WHEEL A 80 I 5 V WILL BE USED FOR EXTERNAL CYLINDRICAL GRINDING

GRINDING WHEEL A 80 J 5 V WILL BE USED FOR INTERNAL CYLINDRICAL GRINDING

GRINDING FOR CONVEX PORTION HAS TO BE DONE ALONG THE CURVE
X**2 + Y**2 + (-5.0)*X + (1.2)*Y + (0.0) =0

GRINDING WHEEL SELECTION

CAPP OF FINE GRINDING

èëë£
¤3. EXTERNAL GRINDING FOR CONVEX PORTION AND SURFACE GRINDING ¤
¤ FOR CONCAVE PORTION HAS TO BE DONE ON SURFACE NO. : 3 ¤
àëëë¥

GRINDING WHEEL A 60 I 5 V WILL BE USED FOR EXTERNAL CYLINDRICAL GRINDING

GRINDING WHEEL A 60 J 5 V WILL BE USED FOR SURFACE GRINDING

GRINDING FOR CONCAVE PORTION HAS TO BE DONE ALONG THE CURVE
X**2 + Y**2 + (-11.0)*X + (39.8)*Y + (28.0) =0
GRINDING FOR CONVEX PORTION HAS TO BE DONE ALONG THE CURVE
X**2 + Y**2 + (-4.0)*X + (2.0)*Y + (0.0) =0

```
CAPP OF FINE GRINDING                                 GRINDING WHEEL SELECTION

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¤4  SURFACE GRINDING HAS TO BE DONE ON THE SURFACE NO.: 4¤
àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

 GRINDING WHEEL A 80 J 5 V WILL BE USED FOR SURFACE  GRINDING
```

```
CAPP OF FINE GRINDING                                 GRINDING WHEEL SELECTION

èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
¤5. SURFACE GRINDING FOR PLANE PORTION AND INTERNAL GRINDING FOR
¤   CONCAVE PORTION HAS TO BE DONE ON SURFACE NO. : 5              ¤
àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

 GRINDING WHEEL A 60 J 5 V WILL BE USED FOR INTERNAL CYLINDRICAL GRINDING


 GRINDING WHEEL A 60 J 5 V WILL BE USED FOR SURFACE GRINDING


 GRINDING FOR CONCAVE PORTION HAS TO BE DONE ALONG THE CURVE
 X**2 + Y**2 + (-13.0)*X + (13.2)*Y + (36.0)  =0




   Do you want to see the result again(y/n):n




   Do you want to run for another workpiece(y/n): n




****************************** O.K. GOODBYE *********************************

********************PRESS ENTER TO GO BACK TO PROGRAM**********************
```


```
********************PRESS ENTER TO GO BACK TO PROGRAM**********************
```

```
Enter the file name for FEATURE RECOGNITION MODULE: test.fet
Enter the file name for WORKPIECE MATERIAL MODULE: test.mat
```

CAPP OF FINE GRINDING OPTIMIZATION

Grinding wheel speed = 30 m/sec.

For surface no.1:

FOR SURFACE GRINDING:-

```
table speed(m/s)      0.2666748
depth of cut(mm)      0.0231912
```

For surface no.2:

FOR EXTERNAL CYLINDRICAL GRINDING:-

```
peripheral speed(m/sec) =  0.2742941
depth of cut(mm)        =  0.0270564
```

For surface no.3:

FOR SURFACE GRINDING:-

```
table speed(m/s)  =  0.2838182
depth of cut(mm)  =  0.0309094
```

FOR EXTERNAL CYLINDRICAL GRINDING:-

```
peripheral speed(m/sec) =  0.2838182
depth of cut(mm)        =  0.0309094
```

For surface no.4:

FOR SURFACE GRINDING:-

```
table speed(m/s)  =  0.2742941
depth of cut(mm)  =  0.0270564
```

For surface no.5:

FOR SURFACE GRINDING:-

```
table speed(m/s)  =  0.2838182
depth of cut(mm)  =  0.0309094
```

CAPP OF FINE GRINDING

FEATURE RECOGNITION

Part name: TEST
Type:- PRISMATIC
Number of surfaces for grinding: 5

Surface no.1: PLANE
WITH_HOLE

Surface finish required: 0.20

Surface no.2: CURVED
CONVEX_WITH_HOLE

Max. height of curve from surface(in cm.) = 3.00
Length of spread of convex portion(in cm.) = 5.00
Surface finish required: 0.30

Surface no.3: CURVED
CONCAVE_AND_CONVEX

Max. depth of curve from surface(in cm.) = 0.80
Length of spread of concave portion(in cm.) = 3.00
Max. height of curve from surface(in cm.) = 2.00
Length of spread of convex portion(in cm.) = 4.00
CONVEX portion is first_in_order.
Surface finish required: 0.40

Surface no.4: PLANE
WITHOUT_HOLE

Surface finish required: 0.30

Surface no.5: PLANE_AND_CURVED_COMBINED
CONCAVE

Max. depth of curve from surface(in cm.) = 3.00
Length of spread of concave portion(in cm.) = 5.00
Length of plane part(in cm.) = 4.00
PLANE_portion is first_in_order.
Surface finish required: 0.40

CAPP FOR FINE GRINDING

WORKPIECE MATERIAL

Part name: TEST
Workpiece code is jk3
Workpiece material: STEEL
Subclass: STAINLESS_STEEL
(AUSTENITIC)

1. SURFACE GRINDING FOR PLANE PORTION AND INTERNAL GRINDING FOR THE HOLE HAS TO BE DONE ON THE SURFACE NO. 1

   GRINDING WHEEL A 80 J 5 V WILL BE USED FOR INTERNAL CYLINDRICAL GRINDING
   GRINDING WHEEL A 80 J 5 V WILL BE USED FOR SURFACE GRINDING

2. EXTERNAL GRINDING FOR CONVEX SURFACE AND INTERNAL GRINDING FOR HOLE HAS TO BE DONE ON SURFACE NO. : 2

   GRINDING WHEEL A 80 I 5 V WILL BE USED FOR EXTERNAL CYLINDRICAL GRINDING
   GRINDING WHEEL A 80 J 5 V WILL BE USED FOR INTERNAL CYLINDRICAL GRINDING

   GRINDING FOR CONVEX PORTION HAS TO BE DONE ALONG THE CURVE
   X**2 + Y**2 + (-5.0)*X + (1.2)*Y + (0.0) =0

3. EXTERNAL GRINDING FOR CONVEX PORTION AND SURFACE GRINDING FOR CONCAVE PORTION HAS TO BE DONE ON SURFACE NO. : 3

   GRINDING WHEEL A 60 I 5 V WILL BE USED FOR EXTERNAL CYLINDRICAL GRINDING
   GRINDING WHEEL A 60 J 5 V WILL BE USED FOR SURFACE GRINDING

   GRINDING FOR CONCAVE PORTION HAS TO BE DONE ALONG THE CURVE
   X**2 + Y**2 + (11.0)*X + (39.8)*Y + (28.0) =0

   GRINDING FOR CONVEX PORTION HAS TO BE DONE ALONG THE CURVE
   X**2 + Y**2 + (-4.0)*X + (2.0)*Y + (0.0) =0

4. SURFACE GRINDING HAS TO BE DONE ON THE SURFACE NO.: 4

   GRINDING WHEEL A 80 J 5 V WILL BE USED FOR SURFACE GRINDING

5. SURFACE GRINDING FOR PLANE PORTION AND INTERNAL GRINDING FOR CONCAVE PORTION HAS TO BE DONE ON SURFACE NO. : 5

   GRINDING WHEEL A 60 J 5 V WILL BE USED FOR INTERNAL CYLINDRICAL GRINDING
   GRINDING WHEEL A 60 J 5 V WILL BE USED FOR SURFACE GRINDING

   GRINDING FOR CONCAVE PORTION HAS TO BE DONE ALONG THE CURVE
   X**2 + Y**2 + (-13.0)*X + (13.2)*Y + (36.0) =0

TEST EXAMPLE NO. 2

AXISYMMETRIC WORKPIECE

COMPUTER - AIDED PROCESS PLANNING

OF FINE GRINDING

by

RAJESH KUMAR BURMAN

```
CAPP FOR FINE GRINDING



        èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
        ¤ 1. FEATURE RECOGNITION               ¤
        ¤ 2. WORKPIECE MATERIAL                ¤
        ¤ 3. GRINDING WHEEL SELECTION          ¤
        ¤ 4. OPTIMIZATION OF GRINDING PARAMETERS ¤
        ¤ 5. OUTPUTS                           ¤
        ¤ 6. EXIT                              ¤
        àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

Enter the selection:1
```

```
CAPP FOR FINE GRINDING

        èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
        ¤ !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! ¤
        ¤         FEATURE RECOGNITION      ¤
        ¤ !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! ¤
        àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

             èëëëëëëëëëëëëëëëëë£
             ¤ 1. NEW PART      ¤
             ¤ 2. EXISTING PART ¤
             ¤ 3. EXIT          ¤
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Enter the selection:1
```

```
èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
¤**********************************************************¤
¤*    THIS MODULE RECEIVES THE INPUTS REGARDING THE TYPE  *¤
¤*    OF PART, TYPE OF SURFACE, ADDITIONAL GEOMETRICAL    *¤
¤*    INFORMATION AND THE SURFACE FINISH REQUIRED.        *¤
¤**********************************************************¤
àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥
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```
CAPP OF FINE GRINDING                                    FEATURE RECOGNITION

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¤*************************************************************¤
¤            FEATURES FOR THE WORKPIECE SURFACES              ¤
¤*************************************************************¤
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        èëëëëëëëëëëëëëëëëëë£
        ¤ TYPE OF PART:- ¤
        àëëëëëëëëëëëëëëëëëë¥

                èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
                ¤      1. PRISMATIC PART          ¤
                ¤      2. AXI SYMMETRIC PART      ¤
                ¤      3. EXIT                    ¤
                àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥
PART NAME(max 10 letters) : axi_test
Enter the feature code :2

Please note: MAX. NUMBER OF SURFACES FOR GRINDING =3

Enter the number of surfaces for grinding:3
```

```
CAPP OF FINE GRINDING                                    FEATURE RECOGNITION

      èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
      ¤ @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@ ¤
      ¤   ADDITIONAL INFORMATION ABOUT AXI-SYMMETRIC SURFACES      ¤
      ¤ @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@ ¤
      àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

Surface no.1 (Cylindrical)

                 èëëëëëëëëëëëëëëëëëëëëëë£
                 ¤  1.WITH HOLES         ¤
                 ¤  2.WITHOUT HOLES      ¤
                 ¤  3.EXIT               ¤
                 àëëëëëëëëëëëëëëëëëëëëëë¥

Enter the code for axisymmetric surface     :1

Enter the surface finish required(microns) :0.2
```

```
CAPP OF FINE GRINDING                                    FEATURE RECOGNITION

      èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
      ¤ @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@ ¤
      ¤   ADDITIONAL INFORMATION ABOUT AXI-SYMMETRIC SURFACES            ¤
      ¤ @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@ ¤
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Surface no.2 (Lateral)

                    èëëëëëëëëëëëëëëëëëëëëë£
                    ¤  1.WITH HOLES       ¤
                    ¤  2.WITHOUT HOLES    ¤
                    ¤  3.EXIT             ¤
                    àëëëëëëëëëëëëëëëëëëëëë¥

 Enter the code for axisymmetric surface    :2

 Enter the surface finish required(microns) :0.3

CAPP OF FINE GRINDING                                    FEATURE RECOGNITION

      èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
      ¤ @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@ ¤
      ¤   ADDITIONAL INFORMATION ABOUT AXI-SYMMETRIC SURFACES            ¤
      ¤ @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@ ¤
      àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

Surface no.3 (Lateral)

                    èëëëëëëëëëëëëëëëëëëëëë£
                    ¤  1.WITH HOLES       ¤
                    ¤  2.WITHOUT HOLES    ¤
                    ¤  3.EXIT             ¤
                    àëëëëëëëëëëëëëëëëëëëëë¥

 Enter the code for axisymmetric surface    :2

 Enter the surface finish required(microns) :0.4

 ENTER DIMENSIONS :

         LENGTH(cm):8.0

         RADIUS(cm):1.0

            OUTPUTS OF FEATURE RECOGNITION MODULE SAVED IN ''axi_test.fet

 Do you want to take the printout(y/n)
 Enter 'y' or 'n'n
```

```
CAPP OF FINE GRINDING                                    WORKPIECE MATERIAL

   èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
   ¤ ********************************************** ¤
   ¤   FOLLOWING MAJOR TYPES OF WORKPIECE MATERIALS  ¤
   ¤   ARE AVAILABLE IN THE DATABASE                 ¤
   ¤ ********************************************** ¤
   àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

            èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
            ¤      a.ALLOYS                    ¤
            ¤      b.ALNICO                    ¤
            ¤      c.ALUMINIUM                 ¤
            ¤      d.BRASS                     ¤
            ¤      e.BRONZE                    ¤
            ¤      f.CAST IRON                 ¤
            ¤      g.COPPER                    ¤
            ¤      h.MONEL METAL               ¤
            ¤      i.NIMONIC                   ¤
            ¤      j.STEEL                     ¤
            ¤      k.TUNGSTEN CARBIDE          ¤
            ¤      l.EXIT                      ¤
            àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥
 Enter the letter code for workpiece material: j
```

```
CAPP OF FINE GRINDING                                    WORKPIECE MATERIAL

   èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
   ¤ ****************************************************** ¤
   ¤   FOR THE MAJOR TYPE OF WORKPIECE MATERIAL SELECTED,   ¤
   ¤   FOLLOWING SUBCLASSES ARE AVAILABLE IN THE DATABASE   ¤
   ¤ ****************************************************** ¤
   àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

            èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
            ¤     a.HARDENED      STEEL        ¤
            ¤     b.SOFT          STEEL        ¤
            ¤     c.HIGH SPEED    STEEL        ¤
            ¤     d.PLAIN CARBON  STEEL        ¤
            ¤     e.ALLOY         STEEL        ¤
            ¤     f.NITRIDING     STEEL        ¤
            ¤     g.HIGH STRENGTH STEEL        ¤
            ¤     h.TOOL          STEEL        ¤
            ¤     i.CAST          STEEL        ¤
            ¤     j.NITRALLOY     STEEL        ¤
            ¤     k.STAINLESS     STEEL        ¤
            àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

 Enter letter code for type of steel: k
```

```
CAPP OF FINE GRINDING                                  WORKPIECE MATERIAL

   èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
   ¤ ************************************************ ¤
   ¤   FOR THE MAJOR TYPE OF STEEL SELECTED, FOLLOWING  ¤
   ¤   SUBCLASSES ARE AVAILABLE IN THE DATABASE         ¤
   ¤ ************************************************ ¤
   âëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

               èëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
               ¤  1.FREE MACHINING           ¤
               ¤  2.FERRITIC                 ¤
               ¤  3.AUSTENITIC               ¤
               ¤  4.MARTENSITIC              ¤
               ¤  5.PRECIPITATION HARDENING  ¤
               ¤  6.OTHERS                   ¤
               âëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥

 Enter number code for type of stainless steel: 3



                        WORKPIECE MATERIAL SAVED IN ''axi_test.mat''

 Do you want to take the printout (y/n):
  Enter 'y' or 'n'n
```

CAPP OF FINE GRINDING GRINDING WHEEL SELECTION

```
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¤1.* EXTERNAL GRINDING FOR THE CYLINDRICAL PORTION AND INTERNAL * ¤
¤   * GRINDING FOR THE HOLE HAS TO BE DONE ON THE WORKPIECE     *¤
àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥
```

GRINDING WHEEL A 80 I 5 V WILL BE USED FOR EXTERNAL CYLINDRICAL GRINDI

GRINDING WHEEL A 80 J 5 V WILL BE USED FOR INTERNAL CYLINDRICAL GRINDI

CAPP OF FINE GRINDING GRINDING WHEEL SELECTION

```
èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
¤2.* SURFACE GRINDING FOR THE LATERAL SURFACE HAS TO BE DONE *  ¤
¤   * ON THE WORKPIECE                                        * ¤
àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥
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GRINDING WHEEL A 80 J 5 V WILL BE USED FOR SURFACE GRINDING

CAPP OF FINE GRINDING GRINDING WHEEL SELECTION

```
èëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë£
¤3.* SURFACE GRINDING FOR THE LATERAL SURFACE HAS TO BE DONE *  ¤
¤   * ON THE WORKPIECE                                        * ¤
àëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëëë¥
```

GRINDING WHEEL A 60 J 5 V WILL BE USED FOR SURFACE GRINDING

Do you want to see the result again(y/n): n

Do you want to run for another workpiece(y/n):n

****************************** O.K. GOODBYE **********************************

*********************PRESS ENTER TO GO BACK TO PROGRAM**********************

*********************PRESS ENTER TO GO BACK TO PROGRAM**********************

```
Enter the file name for FEATURE RECOGNITION MODULE: axi_test.fet
Enter the file name for WORKPIECE MATERIAL MODULE: axi_test.mat
```

```
CAPP OF FINE GRINDING                                    OPTIMIZATION
Grinding wheel speed    30 m/sec.
For surface no.1:

 FOR EXTERNAL_CYLINDRICAL GRINDING:-

  peripheral speed(m/sec)  =  0.2784691
  depth of cut(mm)         =  0.0416638

For surface no.2:

 FOR SURFACE GRINDING:-

  table speed(m/s)  =  0.2742941
  depth of cut(mm)  =  0.0270564

For surface no.3:

 FOR SURFACE GRINDING:-

  table speed(m/s)  =  0.2742941
  depth of cut(mm)  =  0.0270564
```

CAPP OF FINE GRINDING

FEATURE RECOGNITION

Part name: AXI_TEST
Type:- AXISYMMETRIC
Number of surfaces for grinding: 3

Surface no.1 (Cylindrical): WITH_HOLES

Surface finish required: 0.20

Surface no.2 (Lateral): WITHOUT_HOLES

Surface finish required: 0.30

Surface no.3 (Lateral): WITHOUT_HOLES

Surface finish required: 0.40
length(cm) = 8.00
radius(cm) = 1.00

CAPP FOR FINE GRINDING

WORKPIECE MATERIAL

Part name: AXI_TEST
Workpiece code is jk3
Workpiece material: STEEL
Subclass: STAINLESS_STEEL

CAPP OF PROCESS PLANNING

GRINDING WHEEL SELECTION

1. EXTERNAL GRINDING FOR THE CYLINDRICAL PORTION AND INTERNAL GRINDING FOR THE HOLE HAS TO BE DONE ON THE WORKPIECE

   GRINDING WHEEL A 80 I 5 V WILL BE USED FOR EXTERNAL CYLINDRICAL GRINDING
   GRINDING WHEEL A 80 J 5 V WILL BE USED FOR INTERNAL CYLINDRICAL GRINDING

2. SURFACE GRINDING FOR THE LATERAL SURFACE HAS TO BE DONE ON THE WORKPIECE

   GRINDING WHEEL A 80 J 5 V WILL BE USED FOR SURFACE GRINDING

3 SURFACE GRINDING FOR THE LATERAL SURFACE HAS TO BE DONE ON THE WORKPIECE

   GRINDING WHEEL A 60 J 5 V WILL BE USED FOR SURFACE GRINDING

Chapter 5

CONCLUSION AND SCOPE FOR FUTURE WORK

5.1 Conclusion

The proper blend of the knowledge base representation of thumb rules for selecting grinding wheel and an algorithmic approach of optimization model for evaluating grinding parameters appears to have been successful in presenting the complete picture of the process plan.

The validation for the selection of the wheels and the rules associated can not be given in a mathematical form. Since the industry has been flourishing using these thumb rules, it becomes quite obvious that whatever is estimated is more by an educated guess.

The optimization problem solved using the genetic algorithm method resulted in the determination of grinding parameters *viz.* table speed and depth of cut, which are in close agreement with the data available in the literature. Optimizing grinding parameters has resulted in very useful and practical decisions for fine grinding. The figures 4.4-4.9 provide guidelines for the selection of work speed and depth of cut for attaining a particular surface finish for few types of steels. Similar curves can be generated for other materials.

The main limitation in the course of this work has been non-availability of well proven relations for forces, roughness values etc. Many more intrinsic aspects of grinding as a physical process and grinding as a production process have to be still explored and models yet to be furnished.

Due to non-availability of data, optimization could be done only for few types of steels.

5.2 Suggestions for Future Work

1. More data from industry and the authenticated experiments can be gathered for other domains also like stock removal and roughing operations.

2. Graphical interface for work material contour input and suitable algorithms for calculation of length of cut and wheel path generation can be generated.

3. Optimization models for internal cylindrical grinding and centreless grinding can also be developed.

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Appendix A

The following table gives the values of R_1, r, F_1, f, u, V_1 and ν for three types of steels.

Work material	Roughness		Force				Stock removal	
	R_1 (μ m)	r	F_1 (N/mm)	f	μ	u (J/mm^3)	V_1 (mm^3/mm)	ν
100Cr6	2.1	0.38	13	0.33	0.35	60	71	-0.50
4615	4.2	0.29	40	0.98	0.54	42	50	-1.50
316	2.4	0.15	56	0.74	0.35	100	22	-0.51

Appendix B

The following tables show the database used by the system for the selection of grinding wheel. Grit size is selected on the basis of the surface finish required on the workpiece surfaces. Therefore space has been left in its place in the grinding wheel specification.

For external cylindrical grinding:

Work material	Grinding Wheel Specification
Aluminium alloy	A - - H - 5 - V
Copper alloy	A - - N - 5 - V
High-temperature alloy	A - - H - 5 - V
Magnesium alloy	C - - J - 5 - V
Nickel alloy	C - - H - 5 - V
Refractory alloy	C - - J - 5 - V A - - J - 5 - V
Titanium alloy	C - - J - 5 - V
Alnico	A - - L - 5 - V
Aluminium	C - - L - 5 - V
Brass	C - - L - 5 - V
Bronze(Soft)	C - - L - 5 - V
Bronze(Hard)	A - - K - 5 - V
Copper	C - - L - 5 - V
Cast iron	C - - L - 5 - V A - - L - 5 - V
Monel metal	A - - L - 5 - V
Nimonic	A - - J - 5 - V
Hardened steel	A - - K - 5 - V
Soft steel	A - - L - 5 - V
High speed steel	A - - K - 5 - V
Plain carbon steel	A - - K - 5 - V
Alloy steel	A - - J - 5 - V
Nitriding steel	A - - K - 5 - V C - - I - 5 - V
High strength steel	A - - M - 5 - V
Tool steel	A - - K - 5 - V C - - J - 5 - V
Cast steel	A - - K - 5 - V
Nitralloy steel	A - - J - 5 - V
Free machining steel	C - - M - 5 - V
Stainless steel:	
Ferritic	A - - J - 5 - V
Austenitic	A - - I - 5 - V
Martensitic	A - - I - 5 - V
Precipitation hardening	A - - I - 5 - V
Tungsten carbide	C - - J - 5 - V

For internal cylindrical grinding:

Work material	Grinding Wheel Specification
Aluminium alloy	A - - J - 5 - V
Copper alloy	A - - J - 5 - V
High-temperature alloy	A - - J - 5 - V
Magnesium alloy	A - - K - 5 - V
Nickel alloy	A - - J - 5 - V
Refractory alloy	C - - K - 5 - V
	A - - J - 5 - V
Titanium alloy	C - - J - 5 - V
Alnico	A - - L - 5 - V
Aluminium	C - - J - 5 - V
Brass	C - - I - 5 - V
Bronze(Soft)	C - - I - 5 - V
Bronze(Hard)	A - - K - 5 - V
Copper	C - - I - 5 - V
Cast iron	C - - J - 5 - V
	A - - J - 5 - V
Monel metal	A - - L - 5 - V
Nimonic	A - - L - 5 - V
Hardened steel	A - - J - 5 - V
Soft steel	A - - M - 5 - V
High speed steel	A - - J - 5 - V
Plain carbon steel	A - - M - 5 - V
Alloy steel	A - - K - 5 - V
Nitriding steel	A - - K - 5 - V
High strength steel	A - - M - 5 - V
Tool steel	A - - L - 5 - V
Cast steel	A - - M - 5 - V
Nitralloy steel	A - - I - 5 - V
Free machining steel	C - - M - 5 - V
Stainless steel:	
Ferritic	A - - J - 5 - V
Austenitic	A - - J - 5 - V
Martensitic	A - - I - 5 - V
Precipitation hardening	A - - J - 5 - V
Tungsten carbide	C - - J - 5 - V

For surface grinding:

Work material	Grinding Wheel Specification
Aluminium alloy	A - - K - 5 - V
Copper alloy	A - - K - 5 - V
	C - - K - 5 - V
High-temperature alloy	A - - G - 5 - V
Magnesium alloy	A - - K - 5 - V
Nickel alloy	A - - G - 5 - V
	C - - I - 5 - V
Refractory alloy	C - - K - 5 - V
	A - - J - 5 - V
Titanium alloy	C - - J - 5 - V
Alnico	A - - H - 5 - V
Aluminium	C - - L - 5 - V
Brass	C - - I - 5 - V
Bronze(Soft)	C - - I - 5 - V
Bronze(Hard)	A - - J - 5 - V
Copper	C - - I - 5 - V
Cast iron	C - - L - 5 - V
	A - - I - 5 - V
Monel metal	A - - I - 5 - V
Nimonic	A - - J - 5 - V
Hardened steel	A - - J - 5 - B
	A - - I - 5 - V
Soft steel	A - - K - 5 - B
	A - - J - 5 - V
High speed steel	A - - H - 5 - V
Plain carbon steel	A - - J - 5 - V
Alloy steel	A - - I - 5 - V
Nitriding steel	A - - H - 5 - V
High strength steel	A - - J - 5 - V
Tool steel	A - - I - 5 - V
Cast steel	A - - I - 5 - V
Nitralloy steel	A - - H - 5 - V
Free machining steel	A - - H - 5 - V
Stainless steel:	
Ferritic	A - - I - 5 - V
Austenitic	A - - J - 5 - V
Martensitic	A - - J - 5 - V
Precipitation hardening	A - - H - 5 - V
Tungsten carbide	C - - I - 5 - V

For centreless grinding:

Work material	Grinding Wheel Specification
Aluminium alloy	C - - J - 5 - V
Copper alloy	A - - L - 5 - V
High-temperature alloy	A - - J - 5 - V
Magnesium alloy	A - - J - 5 - V
	C - - K - 5 - V
Nickel alloy	A - - L - 5 - V
Refractory alloy	C - - J - 5 - V
	A - - J - 5 - V
Titanium alloy	C - - J - 5 - V
Alnico	A - - H - 5 - V
Aluminium	C - - L - 5 - V
Brass	C - - L - 5 - V
Bronze(Soft)	C - - L - 5 - V
Bronze(Hard)	A - - N - 5 - V
Copper	C - - L - 5 - V
Cast iron	C - - N - 5 - V
	A - - J - 5 - V
Monel metal	A - - I - 5 - V
Nimonic	A - - J - 5 - V
Hardened steel	A - - T - 5 - R
	A - - L - 5 - V
Soft steel	A - - N - 5 - V
High speed steel	A - - L - 5 - V
Plain carbon steel	A - - M - 5 - V
Alloy steel	A - - M - 5 - V
Nitriding steel	A - - M - 5 - V
	A - - I - 5 - V
High strength steel	A - - M - 5 - V
Tool steel	A - - M - 5 - V
Cast steel	A - - M - 5 - V
Nitralloy steel	A - - J - 5 - V
Free machining steel	C - - M - 5 - V
Stainless steel:	
Ferritic	A - - K - 5 - V
Austenitic	A - - K - 5 - V
Martensitic	A - - L - 5 - V
Precipitation hardening	A - - L - 5 - V
Tungsten carbide	C - - J - 5 - V